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Toward Sustainable Use of Space: Economic, Technological, and Legal Perspectives

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A B S T R A C T

During the last few years, the amount of space debris has been frequently mentioned as a potential risk to current and future space operations. The purpose of this article was to describe the discussions held at the First Sustainable Space Economy Workshop held in Finland 2019. The workshop gathered together experts with economic, legal, regulatory, technological, and environmental backgrounds, with an aim of discussing the sustainable use of space from all these perspectives. As an outcome of these discussions, we find that two concepts, satellite sustainability footprint and orbital capacity, should be introduced at an international level. The satellite sustainability footprint measures how likely the satellite stays healthy and operating, without causing risks to self or others. The orbit capacity is essentially an integral of the footprint over an orbit, and it determines how many satellites of different footprints could be launched to the same orbit. In addition, in this article, we discuss how to realize such concepts within the current normative framework. The authors suggest both top-down and bottom-up approaches, necessitating negotiations within an intergovernmental framework and with the relevant space actors. The most important finding of the workshop and this article, however, is that different space-related fields and experts having diverse backgrounds should continuously discuss in a constructive and informal manner to realize the sustainable utilization of space in practice.
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Contents

1. Introduction 2
2. Legal perspectives on the sustainable use of outer space 3
   2.1. Introduction 3
   2.2. Provisions relating to space sustainability in the UN space treaties 3
   2.3. Regulating sustainable use of outer space—the role of nonlegally binding instruments 4
3. Policy perspectives of sustainable use of space 5

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4. Technical perspective of sustainable use of space ... 6
4.1. Flight safety ... 6
4.2. Satellite sustainability footprint ... 7
4.2.1. Maneuverability ... 7
4.2.2. Life expectancy ... 7
4.2.3. Radio frequency interference ... 7
4.2.4. Reliability of the design, launch, and operations ... 8
4.2.5. Similar efforts ... 8
4.3. Quantifying the satellite sustainability footprint ... 8
5. Economic perspective of sustainable use of space ... 9
5.1. Defining orbit capacity ... 9
5.2. Allocation under common-pool resource conditions ... 9
5.3. General principles ... 10
6. Concluding remarks ... 10
Declaration of competing interest ... 11
References ... 11

1. Introduction

This article conveys a summary of discussions within the *First Sustainable Space Economy Workshop* held in January 2019 in Finland. The purpose of the workshop was to focus on the issue of space debris and to investigate the concept of "sustainability of outer space" from different perspectives. The workshop gathered together representatives of technical, legal, regulatory, and economical fields. The founding idea was to begin by introducing the understanding each discipline has on the meaning of "sustainability of outer space." After this, discussions and exchanges were held in mixed group settings combining the approaches, with a goal to arrive at a common understanding of the meaning of sustainability within space activities and to define the potential hurdles that may prevent the realization of sustainable outer space. This article summarizes these discussions combining legal, economic, and technological viewpoints.

With an increasing number of rocket launches, the issue of space debris is a growing concern. Each new launch creates more than one debris object, and the spacecraft itself eventually becomes a debris object, if it is not deorbited at the end of the mission. Less than 10% of the objects launched to low-Earth orbit (LEO) in the last 15 years have been successfully maneuvered with the aim of removing them from their orbital regime [1]. Most LEO missions rely on decades-long natural decay to vacate the orbital slot they have occupied. The spacecraft on the Geostationary Earth Orbit (GEO) are regularly moved to a graveyard orbit at the end of mission; however, as the objects still remain in space, the total amount of debris is not decreased as a consequence. Collisions and even missile-based explosions [2] are increasingly contributing to the debris population growth. While indeed the first predictions of the extent of the space debris problem were already carried out in 1978 [3], the severity of the situation has become more evident in recent years with the increasing number of space objects, especially by commercial actors. As a consequence, the LEO orbits are becoming especially crowded [4].

Concomitantly, especially during the last decade, the issue of sustainable use of outer space has been in the focus of attention in various fields, but the fusion of knowledge between the fields has been lacking. One of the aims of the workshop was to host transdisciplinary discussions, and to bring also economics onboard. We find that the economic issues in relation to space sustainability have so far been considered mostly from the individual companies' viewpoint [5] or by computing the cost of debris [6]. However, to our understanding, the field of economics in relation to space sustainability has not received as much attention in the current discussion. In addition, before markets for space debris mitigation and remediation services could be established, legal and regulatory questions should be answered, including, How to incentivize and enforce space debris mitigation or remediation? How to effectively monitor these actions and quantitatively assess whether they enable sufficient use of the Earth orbits in the future? If these measures do not suffice or do not prove to be economically viable, how to design a regulatory system that efficiently and fairly allocates usable orbital slots to current and future missions?

The article is organized according to the flow of discussions in the First Sustainable Space Economy Workshop. First, the article looks at how the concept of sustainability is viewed within the current legal framework in Section 2. Section 3 introduces how the sustainable use of space is currently taken into account in different space policies and national space legislation. Section 4 summarizes what does the sustainable use of space mean in terms of safe spaceflight and anthropogenic space object (ASO). Section 4 also introduces, as the first outcome of the discussions held in the First Sustainable Space Economy Workshop, a concept termed the "satellite sustainability footprint." Section 5 first lays general definition of the sustainability within the field of economy and then introduces the second outcome of the workshop: the concept of "orbit capacity" as a possible way forward to improve the current situation. In addition to addressing the concepts of "satellite sustainability footprint" and "orbit capacity," each section is to be considered as a standalone contribution written from the viewpoint of the respective field. Section 6 makes an attempt to fuse the fields together and ends the article with some conclusive remarks. The purpose of the article is to initiate discussion and suggest new research with interdisciplinary focus and inspire the community to work further with the technical definitions relating to the issues presented.

2. Legal perspectives on the sustainable use of outer space

2.1. Introduction

The United Nation's (UN) treaties on outer space (UN space treaties)[1] create the international legal framework for human space activities. Although the extent of their acceptance by States varies (as evidenced by the degree of ratification),[2] the UN space treaties form the cornerstones of international space law and the primary international legal source for the governance of outer space activities.[3] Multilateral lawmaking in the form of treaties negotiated under the auspices of the UN has, however, for various reasons, come to a virtual standstill after the conclusion of the Moon Agreement. Instead, nonlegally binding instruments produced by UN COPUOS[4] and adopted by the UN General Assembly have further developed the understanding of the space law principles.[5] These, together with other "soft law" instruments developed outside the sphere of the UN COPUOS, have an increasingly important role in guiding the behavior of space actors. The character of these nonlegally binding instruments is heterogeneous, and their recognition and implementation remain voluntary.[6]

With the increase of nonlegally binding guidelines and standards, there has been a significant interest by States to enact national space laws. In addition to creating a legally binding framework for conducting space activities under a national jurisdiction, national space laws also take on a bridging role between international and domestic laws, as well as between legal obligations and "soft law." Norms of nonlegally binding character can be "incorporated" in national space laws to become legally binding and enforceable within the State's jurisdiction. A practical example relating to sustainability is space debris mitigation. Although virtually all rules to reduce the proliferation of space debris are voluntary and technical in nature, many national legislators have taken those up and turned them into binding licensing conditions at the national level (see a study by Tapio and Soucek [10]). Considering that space activities by their very nature take place in an area beyond national jurisdiction,[7] both international law and national regulation, law and "soft law," are arguably contributing, in their own way, to the setting of common goals and trying to ensure that they are adhered to by all space actors at large.

2.2. Provisions relating to space sustainability in the UN space treaties

The UN space treaties do not specifically address the concept of "sustainability" as such or provide a definition of the term. Nevertheless, although sustainability is not expressly termed as such, it would fall short of the UN space treaties' spirit to deny that they would not include any forward-looking, environmental concern altogether. The drive toward usability, responsible behavior, and risk limitation in outer space activities is an important foundational principle underlying safe and sustainable use of outer space and falls clearly within the UN space treaties' ambit.[8]

Consequently, the OST does contain provisions that are relevant and applicable to the modern international debate on space sustainability and should therefore be taken into due consideration in this discussion. For example, its Preamble refers to the "common interest of all mankind in the progress of the exploration and use of outer space for peaceful purposes."[9] Although the Preamble is not legally binding, it does create certain legal effects. In addition, Article IX of the OST establishes an obligation to avoid harmful contamination of outer space, including the Moon and other celestial bodies, and to avoid harmful interference with the activities of other States.[10] Whether such provisions are entirely utilitarian driven or

[1] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies, entered into force October 10, 1967: 610 UNTS 205 (Outer Space Treaty, OST); Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space, entered into force December 3, 1968: 672 UNTS 119; Convention on International Liability for Damage Caused by Space Objects, entered into force September 1, 1972: 961 UNTS 187 (Liability Convention); Convention on Registration of Objects Launched into Outer Space, entered into force September 15, 1976: 1023 UNTS 15; Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, entered into force July 11, 1984: 1363 UNTS 3 (Moon Agreement).

[2] For the status of State ratifications of the five UN space treaties, see UN office for Outer Space Affairs, Status of International Agreements relating to Activities in Outer Space https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/status/index.html (accessed April 6, 2020).

[3] The Moon Agreement has not been widely ratified, and consequently, its effects may be considered less significant.

[4] 'The Principles Resolutions: Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting, UNGA Res A/RES/37/92 (December 10, 1982); Principles Relating to Remote Sensing of the Earth from Outer Space, UNGA Res A/RES/41/65 (December 3, 1986); Principles Relevant to the Use of Nuclear Power Sources in Outer Space, UNGA Res A/RES/47/68 (December 14, 1992); Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries, UNGA Res A/RES/51/122 (December 13, 1996); The "Practice Resolutions": Recommendations on National Legislation Relevant to the Peaceful Exploration and Use of Outer Space, UNGA Res A/RES/68/74 (December 11, 2013); Application of the Concept of the "Launching State," UNGA Res A/RES/59/115 (January 25, 2005); and Recommendations on Enhancing the Practice of States and International Intergovernmental Organizations in Registering Space Objects, UNGA Res A/RES/62/101 (January 10, 2008); As most recent examples the "Guidelines Resolutions" that also relate to space sustainability: United Nations Committee on the Peaceful Uses of Outer Space, Guidelines for the long-term sustainability of outer space activities, report by the committee, annex ii, 2019. A/74/20, July 3, 2019 (LTS Guidelines); the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, endorsed by the UNGA in 2007 as an annex to the International Cooperation in the Peaceful Uses of Outer Space, UNGA Res A/RES/62/217 (December 22, 2007; UN COPUOS Space Debris Mitigation Guidelines).

[5] For detailed discussion of soft law in the context of space activities, see, for example, various authors in Marboe [7], Tronchetti [8], and Freeland [9].

[6] See Tapio and Soucek [10], especially in the context of space debris mitigation Soucek and Tapio [11].

[7] In this context, see, for example, the topical discussion relating to the legal aspects of (commercial) use of space resources sparked by the United States "Executive Order on Encouraging International Support for the Recovery and Use of Space Resources," issued on April 6, 2020. Available at https://www.whitehouse.gov/presidential-actions/executive-order-encouraging-international-support-recovery-use-space-resources/(accessed April 19, 2020), and the subsequent nonlegally binding Artemis Accords, for reference, see https://www.state.gov/dipnote-u-s-department-of-state-official-blog/space-exploration-and-the-artemis-accords/ (accessed November 25, 2020).

[8] For example, Article VI of the OST; some have concluded that "responsibility" is a precondition to "sustainability"; for discussion on the meaning of "responsibility", see, for example, Rathgeber [12].

[9] OST, Preamble, second substantive para.

[10] OST, Article IX "In the exploration and use of outer space, including the Moon and other celestial bodies, States Parties to the Treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty. States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose. If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the Moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment A State Party to the Treaty, which has reason to believe that an activity or experiment planned by another State Party in outer space, including the Moon and other celestial bodies, would cause potentially harmful interference with activities in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, may request consultation concerning the activity or experiment."

contain at least a nucleus of environmental and intergenerational concern, must be left to in-depth analysis.[11] However, the UN space treaties were drafted a decade before the advent of the notions of "environment" and "sustainability" at the international stage, most notably with the Stockholm Declaration of 1972.[12]

Moreover, Article I of the OST establishes the freedom of using and exploring outer space, including the Moon and other celestial bodies.[13] This freedom is inherent to sustainability, and vice versa; however, similar to other freedoms granted by the OST, it is not absolute. The right is necessarily limited by the requirement to afford the others the same right. Moreover, the rights are to be interpreted in the light of the treaty's other principles, such as cooperation and information sharing (e.g. registration),[14] notions frequently mentioned in the space sustainability debate. There is, however, no legally binding obligations to be derived from these rules concerning space sustainability as such. Therefore, the relation between the freedom of exploration and the use of outer space and the method of orbital capacity discussed in this article will have to be carefully addressed. Although the freedom of Article I of the OST is not absolute, it cannot be restricted by some States either, not even by the States Parties to the OST.[15] Restrictions, if any, would have to be decided on the broadest possible level "without discrimination of any kind, on the basis of equality."[16] In the past, ideas such as taxation or fee systems to provide for financial resources to tackle space debris have frequently, and consistently, been challenged with reference to the fundamental space freedoms.

In addition, in any interpretation[17] of the UN space treaties, be that environmental or use oriented, one must take into account the founding notions of a State's international responsibility and liability. These are especially pertinent when discussing private space activities. Article VI of the OST sets out the basic requirement that the States are required to oversee that the national space activities, including those of its nongovernmental entities, are conducted in accordance with international law.[18] In addition, Article VII sets out a related notion advocating that it is the launching State, which is liable for damages caused by space objects.[19] As such, those provisions have relevance to the current discussion on the sustainability of space activities, especially taking into account the novel uses and increasing number of nongovernmental actors in outer space. The OST requires its State parties to authorize and continuously supervise the activities of nongovernmental space actors, but it does not prescribe the form or other conditions to do so.[20]

As noted, in recent years, there has been an increase in the number of national space laws.[21] Concomitantly, there has been a growing interest and need to develop the governance of space activities through nonlegally binding instruments. Although these two trends have emerged independently, and not necessarily as a consequence of one and other, they are nevertheless necessarily interlinked and together contribute to the development of space law at large. The defining character of the nonlegally binding instruments is rather evident—they lack the enforcement mechanisms available to law, while space actors due to various reasons may follow them (including moral, political reasons, or self-interest by industry), but without legal force. To achieve enforceability, nonlegally binding instruments necessitate a deliberate change in the character of the instrument, which can be achieved by incorporating these "soft law" instruments in national, legally binding instruments—especially through national space laws. Such confluence of normative spheres comes with certain challenges. Although law has a distinct advantage in terms of steering behavior, soft law starts from the premise that space actors voluntarily take on what is established therein, and desired behavior becomes normative, and addressed at the national level, that is, within their jurisdictional powers (see deeper discussion in a study by Tapio and Soucek [10]).

2.3. Regulating sustainable use of outer space—the role of nonlegally binding instruments

In the absence of detailed and specific regulation in the UN space treaties, the question arises, what are the best possibilities to further develop the legal (and thus, ultimately, behavioral) framework for space activities—including the question on space sustainability. The most evident aspect of space sustainability and the corresponding norms of responsible behavior in outer space, discussed and regulated over the past two decades, concerns space debris mitigation. The realization that an uncontrolled and uncoordinated increase of the orbital debris population would negatively affect space activities of all space actors—governmental and private, established or new—led to progressive regulatory action.

The first step toward behavioral management was not the creation of law; however, the issuing of the Space Debris Mitigation Guidelines of the Inter-Agency Space Debris Coordination Committee (IADC)[22] brought a nonlegally binding collection of technical recommendations—or guidelines, to life, which later served as the

[11] For comprehensive take on the environmental issues relating to outer space see, for example, Viikari [13] and Viikari [14].

[12] United Nations General Assembly, United nations conference on the human environment, 1972. A/RES/2994, December 15, 1972, https://www.refworld.org/docid/3b00f1c840.html.

[13] Article I of the OST "… Exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind."

[14] See especially Articles VIII, IX, XI, and XII of the OST.

[15] "It is important to note the way in which these rights are formulated in Art. I. The rights are rights of all states, not just rights mutually recognized by the parties of the OST and restricted to them. (…) Each state/country may explore and use outer space." Lyall and Larsen [15], page 60.

[16] Article I of the OST.

[17] As an international treaty, only its State Parties have the right to legally interpret the treaty text.

[18] Article VI of the OST: "States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty. When activities are carried on in outer space, including the Moon and other celestial bodies, by an international organization, responsibility for compliance with this Treaty shall be borne both by the international organization and by the States Parties to the Treaty participating in such organization."

[19] Article VII of the OST: "Each State Party to the Treaty that launches or procures the launching of an object into outer space, including the Moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object or its component parts on the Earth, in air space or in outer space, including the Moon and other celestial bodies." The issue of liability for damages is further elaborated and specified in the Liability Convention.

[20] Article VI of the OST; it has been submitted that Article VI of the OST sets a directive that must be achieved through "adequate means," including, but not necessarily confined to, legislative action at national level, Gerhard [16], page 119.

[21] Especially with reference to European States, currently 12 of 22 ESA Member States have a national space law (Norway, Sweden, Finland, Denmark, the Netherlands, Belgium, Luxembourg, France, Austria, the United Kingdom, Portugal, and Greece). Many of these have been promulgated or subject to update in the recent years.

[22] The first set of guidelines were issued in 2002 and later revised in 2007; IADC is an international forum of governmental bodies for the coordination of activities related to the issues of man-made and natural debris in space, Foreword, IADC Space Debris Mitigation Guidelines, IADC-02-01, Revision September 1, 2007.

basis for other, still nonlegally binding instruments, including the COPUOS Space Debris Mitigation Guidelines.[23] It was only with the proliferation of modern national space laws that the obligation of mitigation of space debris progressively found its way into binding law. Today, many national space acts include appropriate space debris mitigation measures as an element of the licensing requirements to their nongovernmental space actors. The various technical guidelines are thereby often incorporated by means of (more or less specific) references in national regulation. A special interconnection between technical norms and positive law is made in cases where a national law refers to a nonlegally binding instrument as a "state of the art" requirement. The practical and legal issues that may arise from this coupling are not always necessarily foreseen (especially in the context of space debris mitigation, see a study by Soucek and Tapio [11]).

As can be recalled, following a broad debate on space debris, the overarching notion of "space sustainability" finally came under the spotlight of intergovernmental attention when, in 2010,[24] the UN COPUOS started to deliberate on the guidelines concerning space sustainability in a holistic manner in a multilateral setting. It triggered, for the first time during the space age, a vivid exchange and consensus building process on principles that should lead toward more safe and sustainable use of outer space. Highlighting the political considerations underpinning space sustainability, this process lasted a decade and resulted in the adoption of Guidelines for the Long-term Sustainability of Outer Space Activities (LTS Guidelines) by UN COPUOS in 2019.[25]

The currently agreed 21 LTS Guidelines and their preamble are the result of widespread and multidisciplinary engagement. The LTS Guidelines deal with various aspects relating to space sustainability and, in this context, provide the following definition of long-term sustainability: "the ability to maintain the conduct of space activities indefinitely into the future in a manner that realizes the objectives of equitable access to the benefits of the exploration and use of outer space for peaceful purposes, in order to meet the needs of the present generations while preserving the outer space environment for future generations."[26] Although some of the LTS Guidelines reflect existing legally binding norms or widespread practice, others are more forward-looking innovations. Many nevertheless consider that there are important areas uncovered, most notably relating to space debris remediation and close proximity operations, the inclusion of which may yet find its way once the UN COPUOS resolves the procedural way to forward these open issues.[27]

Still, at best, the LTS Guidelines will add another element to the plethora of "soft law" provisions that have emerged ever since treaty making on space activities came to a standstill in the 1980s. An international legal—that is, *enforceable*—obligation to reach and maintain orbital sustainability will therefore remain science fiction for the near to midterm future. However, this does not mean that law and policy could not serve to reach exactly that purpose through other means and methods. Without entirely canceling out the possibility of regaining the treaty-making momentum, the nonlegally binding instruments and their application and enforcements through national space laws currently represent the best way forward in safeguarding sustainable space activities.

In summary, it is noted that apart from the LTS Guidelines, the current UN space treaties do not lay a binding, international legal framework for the sustainable use of outer space, including the Earth orbits. The LTS Guidelines are "soft law" and not legally binding. It may well be questioned whether the existing "soft law" provisions are relevant and adequate to promote sustainability and whether national implementation of those guidelines may lead to diverging practice among space-faring states instead of welcomed concerted practice, especially when taking into account future technical solutions, for example, docking. Much will depend on the States' willingness and resources in the national implementation process, which differs between the well-established and emerging space-faring States.[28] The current legal practice may lead to questions as to whether the route to interpret, apply, and enforce space sustainability through national legislation is the optimal way to solve the issue or if a binding regulation at the international level is necessary to uniformly regulate and thus avoid local solutions to a global problem.

3. Policy perspectives of sustainable use of space

As discussed in the First Sustainable Space Economy Workshop, several national strategies and policies recognize the need to address and ensure the sustainable use of outer space through space policy measures. Active updates of space policies pave the way to further steps to ensure sustainability through national legislation, international collaboration, technological development, and financial instruments. In the European context, sustainable use of outer space is currently getting more recognition. For example, in 2016, the European Commission adopted a Communication on a Space Strategy for Europe,[29] noting that space is becoming a more challenging environment and recognizing the proliferation of space debris as the most serious risk to the sustainability of space activities. Therefore, the Strategy urges to ensure the protection and resilience of critical European space infrastructure. As an example, the EU space surveillance and tracking (SST) support framework responds to the issue of space debris. The proposal for regulation establishing the EU Space Programme[30] extends the SST framework to Space Situational Awareness (SSA) to address space weather and near-Earth objects. The Strategy also urges the Member States to promote international principles of responsible behavior in outer space in the framework of the United Nations and other appropriate multilateral fora and in line with the UN space treaties.

In the United States, a Space Policy Directive 3 (SPD-3) on National Space Traffic Management (STM) Policy was signed on June

[23] Committee on the Peaceful Uses of Outer Space, Space debris mitigation guidelines, 2007. Endorsed by the United Nations General Assembly as an annex to the International Cooperation in the Peaceful Uses of Outer Space, December 22, 2007, UNGA Res A/RES/62/217.

[24] Committee on the Peaceful Uses of Outer Space, Report of the scientific and technical subcommittee on its 47th session, 2010. Vienna, February 8–19, 2010, A/AC.105/958, paragraph 181.

[25] United Nations Committee on the Peaceful Uses of Outer Space, Guidelines for the long-term sustainability of outer space activities, report by the committee, annex ii, 2019. A/74/20, July 3, 2019, http://www.unoosa.org/res/oosadoc/data/documents/2019/aac_105c_1l/aac_105c_1l_366_0_html/V1805022.pdf. The LTS Guidelines were "welcomed with appreciation" by the UN General Assembly in the yearly "omnibus resolution" pertaining to International Cooperation in the Peaceful Uses of Outer Space, UN General Assembly, Resolution adopted by the General Assembly on December 13, 2019, 74th session, A/A/RES/74/82.

[26] LTS Guidelines, Preamble, I Context of the guidelines for the long-term sustainability of outer space activities, para. 5.

[27] United Nations Committee on the Peaceful Uses of Outer Space, Guidelines for the long-term sustainability of outer space activities, report by the committee 2019, especially paragraphs 165–168; These paragraphs envisage the establishment of a dedicated working group, which is at the time of review of this article in November 2020 still in progress.

[28] For discussion on legal and regulatory aspects on the LTS Guidelines, see, for example, Martinez [17]; Martinez and et al. [18].

[29] https://ec.europa.eu/transparency/regdoc/rep/1/2016/EN/COM-2016-705-F1-EN-MAIN.PDF.

[30] https://www.consilium.europa.eu/en/press/press-releases/2019/03/13/eu-shapes-its-future-space-policy-programme/.

18, 2018.[31] It provides direction toward a safe and secure environment for increasing commercial and civil space activities. An implementing bill is under the legislative process. The aim of the initiative is to set priorities for SSA and STM innovations and encourage the growth of the US commercial space sector, incorporate national security considerations, establish an updated STM architecture, and promote space safety standards and best practices across the international community. The initiative considers space safety as a global challenge and stresses the need for international transparency and STM data sharing. As required by SPD-3, the US National Space Council announced in December 2019 an update to the US Government Orbital Debris Mitigation Standard Practices,[32] which were originally published in 2001. This update includes improvements to the original objectives, clarification, and additional standard practices for certain classes of space operations with the aim to promote efficient and effective space safety practices and long-term sustainability of outer space.

Space safety and security is also one of the four pillars of the activities of the European Space Agency, with the objective to mitigate and prevent the impact from hazards from space. At Space19+ in 2019, ESA's Ministerial Council agreed to established Space Safety as a new program with more than four times larger budget than its predecessor SSA program.[33,34] As a concrete action, the ministers agreed to commission the world's first space mission to remove an item of debris from orbit, ClearSpace-1, planned for launch in 2025. The mission is procured as a service contract with a startup-led commercial consortium, promoting a new market for in-orbit servicing and debris removal.

Furthermore, smaller and younger space-faring nations, such as Finland, Sweden, and Denmark, recognize the importance of the sustainable use of outer space in their space policies and space strategies. This is in accordance with economic views on how different actors regard common-pool resources (see also Section 5). For example, the update of the national space strategy of Finland in November 2018 stated as one of its targets for 2025 that companies and research organizations operating in Finland use space sustainably.[35] Furthermore, the Swedish Space Strategy defines the safeguarding of the safe and predictable extraterrestrial environment as a strategic objective.[36] To emphasize the importance of this objective, Sweden aims to contribute toward common efforts to manage the amount of space debris through international participation. Moreover, the national space strategy of Denmark recognizes the opportunities provided by megaconstellations but encourages the government to closely monitor and support international endeavors to mitigate the space debris risk likely to result from increased activity in lower Earth orbit.[37]

Although international and national strategies and policies have been made to emphasize the importance of the sustainable use of space as noted previously, the reality often is a compromise between policy declarations and economic interests. Promoting opportunities of new commercial players as a strategic objective may be more compelling than limiting those opportunities for the sake of more sustainable use of outer space. It could even be argued that such a conflict undermines the impact of space policies. However, the definition of sustainability in the field of economics, "*the current use of space should not negatively affect the potential benefits derivable from the future use of that space*" (see Section 5) as it is risking the future profits, is an important reminder emphasizing sustained economic benefit from space-based operations. Therefore, the possible contradiction between the sustainability declarations and national authorization of commercial mega-constellations can be at least mitigated by the previously mentioned economic definition, as it is in the interest of both governments and operators to ensure the long-term usability of space. Although governments may strengthen their policy statements through binding regulation, self-imposed principles and targets of companies [5] could further the sustainable space policies and provide a clear drive in space technology innovation. Actors such as Space Safety Coalition,[38] a coalition of companies promoting responsible use of space, may become indispensable in the future. Space policies and strategies have their role in stating the objectives and raising awareness while concrete actions are needed to reach those objectives.

4. Technical perspective of sustainable use of space

From a technical perspective, the discussions at the First Sustainable Space Economy Workshop concluded that the practical means to decrease the amount of debris are (1) mitigating the creation of new debris and (2) actively removing existing debris (for a review see, e.g., Ref. [19]). In mitigating debris, two aspects are important. The first aspect is to free the orbit space after the end of the mission by deorbiting the spacecraft,[39] whereas the second is to prolong the lifetime of existing spacecraft, which prevents new debris by decreasing the need to launch more spacecraft.

4.1. Flight safety

In terms of operational flight safety, the risk aspects of space debris to the spacecraft orbital operations can be divided into the following subgroups:

1. Risk that the spacecraft hits another object (operational spacecraft, defunct spacecraft, or debris) and generates space debris.
2. Risk that the spacecraft, for example, due to the inability of performing collision avoidance maneuvers, is hit by an external object (spacecraft or debris), consequently generating space debris.
3. Risk that the spacecraft itself generates space debris due to the abrupt release of energy (e.g. by the explosion of propellant tanks or batteries due to thermal runaway and catastrophic failures of reaction wheels).
4. The risk of a collision with consequent release of debris due to either the absence of rules or critical system failure during collision avoidance operations.

All the previously mentioned items need to be taken into account when assessing the risk of debris generation linked to spacecraft operations. On the first two items, the risk and the

[31] https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/.
[32] https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf.
[33] https://www.esa.int/Newsroom/Press_Releases/ESA_ministers_commit_to_biggest_ever_budget.
[34] https://www.esa.int/Safety_Security/Clean_Space/ESA_commissions_world_s_first_space_debris_removal.
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[36] https://www.government.se/4ad876/contentassets/ea187b8c0a814ac09c36b8a43154eb49/a-strategy-for-swedish-space-activities.pdf.
[37] https://ufm.dk/en/publications/2016/files/space-strategy-2016.pdf.
[38] https://spacesafety.org.
[39] Moving the spacecraft onto a graveyard orbit is not in practice an action freeing orbital space, and it may also lead to potential future problems [20].

associated mitigation methods are related to the spacecraft's capability to (1) accurately track and be aware of all relevant objects in orbit, (2) make very accurate orbit predictions, (3) maneuver the spacecraft, and (4) understand internationally recognized rules for performing collision avoidance maneuvers. Furthermore, the spacecraft's ability to withstand impact and generate as little debris as possible (i.e. robustness) plays a role. Therefore, item (2) needs to be addressed in the context of the spacecraft design process and is an essential part of the preliminary design review of the spacecraft project. The fourth item is especially relevant to safety in the context of close proximity operations, for example, docking. Especially in the future, if in-orbit servicing will be performed to increase the spacecraft lifetime, docking becomes an issue needing international agreements.

However, the locations of the current operational spacecraft are not always known to a great accuracy, even if it seems to be easy to track the positions of ASO. We present a case example using ASTRIAGraph,[40] which collects position information from multiple sources and maps their combined information into a graph database. One of the issues with ASO location knowledge is that the different sources of information about where these objects are located are not always consistent or in agreement, indicating that the information is to be regarded as *an opinion*. Fig. 1 presents an example of the position of Flock CubeSats, owned by Planet. The numbers 1–3 in parentheses indicate different positional information of these CubeSats by US Space Command (USSPACECOM), the owner (Planet), and a commercial radar operator LeoLabs, respectively, whereas number (4) shows the position at which the ASTRIAGraph team believes the object to be (based upon the radar data provided by LeoLabs). The largest distances between objects are of the order of several hundred meters. This example indicates that, for example, for docking purposes, one needs a thorough assessment of where the object is as well as excellent maneuverability to perform a successful operation. Another immediate problem comes from the classified spacecraft, for which the long-term intentions and operational maneuver planning are not shared. Currently, there is no independent, transparent measurement mechanism to know the ASO positions in great detail. However, to define "space traffic management rules," accurate monitoring of space objects is required so that the positions can be quantitatively assessed.

4.2. Satellite sustainability footprint

Even if the locations of the current debris and spacecraft would be known to a great accuracy, orbit safety depends first and foremost on the ability of one single spacecraft to avoid loss, risk to life, and disruption to self and others. In addition, there are uncontrollable factors, such as the space weather conditions, which may lead to harm anyway. This section systematically lists the factors discussed at the First Sustainable Space Economy Workshop, needed to keep the spacecraft healthy in practice. The risk of collision directly depends on these factors, and hence, they can be used to define a "*satellite sustainability footprint*," a concept from the technical spacecraft system point of view.

4.2.1. Maneuverability

Maneuverability may mean either the capability to change the spacecraft position to avoid collision with debris or the capability to deorbit. Deorbiting of the spacecraft can be performed by the following means: (1) gravity-assisted re-entry (with or without drag augmentation); (2) propulsion based deorbiting (chemical, electric, or electrodynamic propulsion); and (3) active debris removal with robotic means (if the spacecraft cannot be commanded to deorbit). Although the enlisted means can all be used to deorbit, from the orbital operations for active collision avoidance point of view, chemical or electric propulsion capability with associated debris detection and attitude and orbit control system capabilities are the only viable options.

The current IADC recommendation [21] is to remove spacecraft from orbit at the latest 25 years after they have completed their mission. This is because of the fact that spacecraft in orbits above a certain altitude will stay in the orbit, in practice, forever unless actively removed. The IADC recommendation was established based on the spacecraft traffic situation at the time of the recommendation. However, the situation is now changing. Klima et al. [22] present an interesting game-theoretical consideration and conclude that if each player removes one high-risk object every 2 years according to player's own interests, the risk of collision will substantially decrease. This indicates that the increasing risk of debris collisions could be mitigated by removing active satellites as soon as they have completed their mission rather than allowing them to stay in orbit for additional time up to 25 years. This calls for both consideration of the 25-year rule as well as active development of the deorbiting technologies.

4.2.2. Life expectancy

One of the most important factors affecting spacecraft health is its ability to tolerate radiation and other environmental conditions called *space weather* that permeates the near-Earth space. Radiation is concentrated into two, sometimes three torus-shaped van Allen belts [23]. Especially in the outer belt, the different energization processes contribute to highly variable fluxes of relativistic electrons [24] that are known to cause single-event upsets and spacecraft anomalies. Particles having higher fluxes of lower energies can cause severe damage because of spacecraft charging [25]. Furthermore, other types of unpredictable space weather can lead to spacecraft failure [26]. LEO spacecraft traverse parts of the van Allen belts four times an orbit, whereas the GEO spacecraft are sometimes continuously embedded within the highly dynamic van Allen belts.

The spacecraft life expectancy is mainly a factor of two aspects: first, the ability to withstand the orbital conditions either by construction or by fault detection and recovery, and second the ability to prolong the spacecraft lifetime, for example, by in-orbit servicing. The spacecraft tolerance toward space weather directly contributes to the life expectancy of a spacecraft, and hence, one factor contributing directly to the sustainability footprint is how long the spacecraft is expected to be healthy to operate and to receive commands within the targeted orbit. A critical factor in the life expectancy is to pass the various tests before the launch and to use components that are known to operate in different orbital conditions. Spacecraft can also be built in such a way that it detects faults and recovers from, for example, radiation-based failures [27]. Life expectancy could also be prolonged by in-orbit servicing, for example, by performing refueling, repairing, upgrading, transporting, and rescuing. Therefore, the ability to dock an in-orbit servicing vehicle would favorably contribute to the life expectancy, assuming that the docking itself does not cause harm. So far, such missions have not been carried out autonomously [28].

4.2.3. Radio frequency interference

Although the spacecraft itself could be healthy and operating in orbit, it cannot be command or it cannot send signals to ground makes it effectively a piece of debris. Conditions leading to this situation could be caused by *radio frequency interference* (RFI), which can occur unintentionally due to space weather

[40] http://astria.tacc.utexas.edu/AstriaGraph.

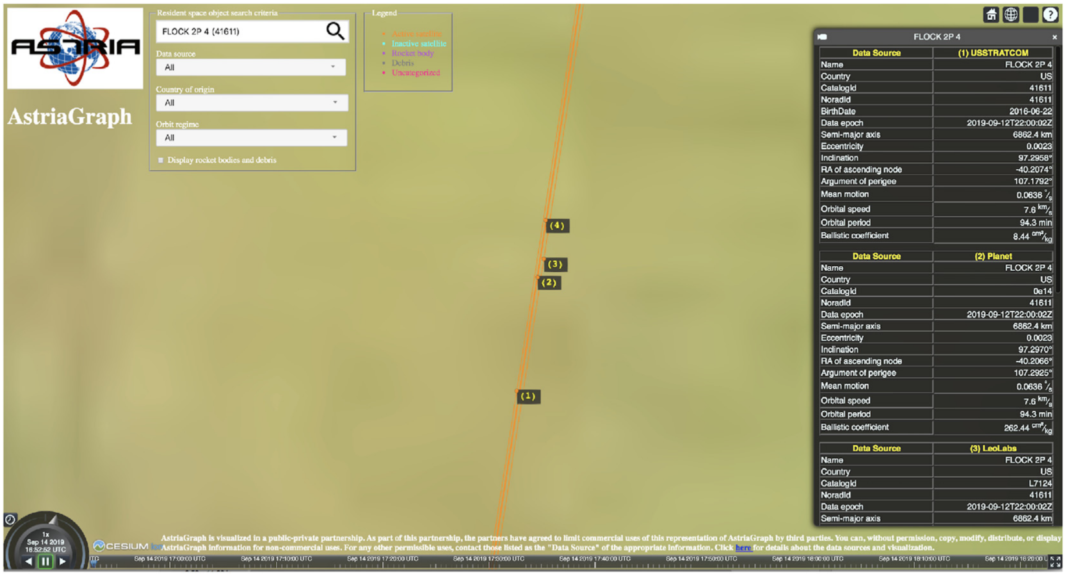

Fig. 1. Case example by ASTRIAGraph. The orange line represents an orbit of an ASO, and the numbers 1–3 indicate the position location for the object based on USSTRATCOM (1), object owner Planet (2), a commercial radar operator LeoLabs (3), respectively. Number (4) indicates the position at which the ASTRIAGraph team believes the object to be, based upon the radar data provided by LeoLabs.

[29,30], congestion of the used communication bandwidths, or intentional jamming of the spacecraft signals. In fact, RFI can be considered as a major cybersecurity threat to satellite operations and is therefore a major concern in the sustainable use of space [31]. Currently, the radio spectrum framework is being managed and regulated by the International Telecommunication Union (ITU).

4.2.4. Reliability of the design, launch, and operations

Other factors that directly contribute to the spacecraft health and therefore the sustainability footprint are as follows:

- Reliability of launch. If everything else in the spacecraft technical design and operation passes the sustainability criteria but the launch fails, especially near the targeted orbit, the spacecraft may remain as piece of debris.
- Predictability of behavior on orbit. This factor is dependent both on the spacecraft construction and its structural integrity, as well as its software and communication with the ground. Robustness in the predictability of behavior is mainly achieved before launch, while environmental contributions, such as space weather, may contribute as well. It is important to identify whether the spacecraft operations are nearing the end of life, indicating that the spacecraft should be commanded to free the allocated orbit space while it is still in good health to do so.
- Size. Large objects are more threatening to the other users of space, and if they collide or break up, others will have a larger debris cloud to handle.

4.2.5. Similar efforts

Before January 2019, concepts close to the satellite sustainability footprint have been promoted by Oltrogge [32] in the 2018 SpaceOps Conference and by Khlystov [33] in 69th International Astronautical Congress held in Bremen 2018. In May 2019, the World Economic Forum announced a team[41] developing a Space Sustainability Rating,[42] which is a score representing a mission's sustainability in relation to international guidelines. It is based on voluntary answers to a questionnaire and promises to evaluate the answers "in combination with other external data through a mathematical model that establishes a rating for the mission." The concept is introduced in Rathnasabapathy et al. [34]. This rating concept is applied for the space environment capacity control by Krag et al. [35]. Furthermore, a similar concept, named Space Traffic Footprint, has been introduced at the UN COPUOS meeting in February 2019 [36].

4.3. Quantifying the satellite sustainability footprint

We noted in the First Sustainable Space Economy Workshop that to succeed in establishing a sustainability footprint definition respected by all space-faring parties, all opinions should be heard in building the footprint; otherwise, it will not be widely respected. Therefore, we do not arrive at a quantitative definition here but merely propose that one should be developed at a suitable international arena trusted by all parties. However, we note that the loose understanding of the footprint is the burden that any given ASO poses on the safety and sustainability of any other ASO and the environment. A minimal satellite sustainability footprint allows self and others to use space safely without risking anyone's operations, whereas a maximal footprint completely prevents self and others from using the specific orbital space. Minimizing the footprint means that the spacecraft itself and its operations must be performed such that degradation or disruption of services is prevented. Even with a minimum footprint, however, other users of space must take it into account for their own safety, and therefore, the risk to others is not negligible. Maximum footprint could be associated to a spacecraft, which breaks up because of any of the reasons mentioned previously.

A possible framework to assess the satellite sustainability footprint is the Life Cycle Assessment (LCA) tool, which is used to qualify environmental impacts of the spacecraft production and

[41] https://www.media.mit.edu/posts/creating-a-space-sustainability-rating/.

[42] https://www.weforum.org/projects/space-sustainability-rating.

operations. This is a tool widely used by the space industry. Attempts to introduce space debris indicators into LCA are currently being carried out by Maury et al. [37], who consider the exposure to space debris and the severity of a potential spacecraft break up to the orbit environment. The satellite sustainability footprint could be a parameter to which all previously mentioned factors contribute, and in practice, it could be an eco-label, agreed by all parties. Furthermore, the satellite sustainability footprint could also include various other environmental perspectives, for example, a carbon footprint per unit of service delivery. Developing footprinting methodologies for satellites could be built on existing—LCA based—approaches for product carbon footprints [38]. A particular challenge is the sharing of information necessary to calculate (and verify) the footprint, for which, among others, blockchain technologies could be used [39]. A quantified satellite footprint creates a measurable concept, which can be used in policies to enhance the sustainable use of space.

5. Economic perspective of sustainable use of space

Our discussions from the perspective of the field of economics at the First Sustainable Space Economy Workshop started from the definition of sustainability. As previously stated, the definition for the sustainable use of space is that the current use of space should not negatively affect the future use of that space. The economic framework for a finite natural or man-made resource is called *common-pool resource* [40,41]. In conjunction with the economic definition of sustainable use of space, a concept called *external effects* is important. A negative external effect means that the considered phenomenon, that is, space debris, causes negative effects on other parties inside or outside the considered system or domain, without compensating the affected parties for these negative effects. For example, debris collisions can harm other satellites, whereas, on the other hand, the debris risk may prevent newly planned satellites to obtain the preferred orbit or to complete their mission, or even reach any orbit at all.

Recently, a few authors [42–44] have started to study the space debris issue casting it as an economic problem of sustainable management of a common-pool resource. Furthermore, efforts based on the choices of individual companies have been introduced, for example, Chrysaki [5] calls for a voluntary code of conduct to be adopted by private companies and industries, with the idea that responsible behavior would increase the company brand, reputation, and ethical investments. The Organization for Economic Co-operation and Development (OECD) has recently assessed the socioeconomic impacts and costs related to space debris [6]. The OECD report [6] concludes that, for example, at GEO, the debris mitigation costs can be 5–10% of the mission costs and even higher at LEO. Furthermore, they call for research into deorbiting and space weather while requesting internationally binding minimum requirements to be developed.

5.1. Defining orbit capacity

The rationale for an economic intervention regarding the use of orbits is that the total capacity of orbits is large but nevertheless *finite*. In economic terms, the definition of capacity can be either based on physical properties (orbits, satellites, and already present debris) or on the aspired aggregate service output and net benefit capacity from those orbits. STM rules have to be based on the physical orbital capacity; however, if value maximization of total orbit endowment is the target, the service capacity needs to be taken into account. If there is no concertation or coordination of individual decision-making, according to economic theory, each actor will try to maximize its total net benefits, which often results in a process, eventually leading to exhaustion of the resource capacity and thereby causing a rise of costs and/or a decrease in benefits (service output). If there is concertation of the actors' decisions, it is in principle possible to attain a maximum level of common-pool resource use, which is still sustainable, thereby maximizing aggregate benefits over a longer period. The switch from individualized to concerted decision-making faces often a social dilemma, as some of the actors will lose compared with a situation without concertation.

The economic approach to orbit capacity offers promising potential for specifying sustainable management of orbital use. It is generally known that management of common-pool resources requires cooperation within sectors and/or regions [40]. The stronger, broader, and clearer the consensus is, the better it guides decision-making in the entire value chain. The satellite sustainability footprint could define the constraints one must take into account in determining capacity so that responsible management of the footprint factors (maneuverability, life expectancy, etc.) all act to decrease the satellite sustainability footprint, indicating that a large number of such spacecraft could be allocated into the same orbit. If the footprint factors are not well managed, and, for example, the spacecraft can turn into a defunct object that cannot be operated by ground commands, this would result in increasing the footprint, and fewer of those spacecraft could be allocated to the same orbit. Under certain market conditions, it can be attractive for incumbent (market dominant) satellite companies not to vacate an orbit despite the dysfunction of the satellite [42]. This is relevant if the consequent reduction in available orbit space causes satellite service prices to rise, which more than compensates for the foregone revenues of an unused satellite slot plus the remaining cost of keeping the dysfunctional satellite.

Quantification of (remaining) orbit space could be envisaged starting from defining the amount of debris, which is still acceptable, for example, to avoid the Kessler syndrome, which predicts a cascade of collisions leading to exponential increase of objects. In this respect, the 850 km sun-synchronous LEO orbit may be nearing its maximum capacity, as the estimated number of potentially fatal debris objects is already around 9000 [45]. The maximum capacity could be understood as the maximum tolerable risk per orbit so that the consequences to other users are minimized. This minimization can be viewed as taking into account the negative effect within the economic theory. The incremental additions to the orbit capacity could be reflected in terms of pathways reaching the inflection point of the Kessler syndrome.

5.2. Allocation under common-pool resource conditions

From an economic perspective, capacity management can be reflected from two viewpoints: (1) operational capacity management and (2) capacity management within the common pool of resources. Operational capacity management [46] is a task of understanding the constraints of different resources used by the operations. In addition, it is about setting and agreeing the effective capacity of any operations in a way it can respond to the demand requirements placed upon it. Capacity management is typically divided into three time-based planning horizons (short-, medium-, and long-term capacity management). Furthermore, capacity management can be based on different degrees of commonality [32]. Typically, the capacity is being planned and managed in aggregated terms. Capacity management can be executed by using cumulative representations and/or queuing theory. Almost all operations have different kinds of fluctuations in forecast and operating demand causing changes in capacity management and decisions over time.

If the involved actors acknowledge the common-pool resource character of orbits, they can consider capacity management [47]: (1) pre-determination of (maximum) aggregated capacity levels and (2) potential (future) incremental additions to predetermined capacity and their decisions points in time. The new time horizons for decisions of incremental capacity is important because typically, the different constraints using the capacities of common-pool resources are known. Ill-structured and inadequate rights, regulatory structures, regional specificities, and other externalities all increase the complexity of capacity management issues among actors that utilize the common-pool resources.

The sustainable management of the orbits as a common-pool resource can take several forms. Yet, all these forms need a consensus on cooperation as a basic prerequisite of the feasibility and acceptability of the management approach. On the one hand, there are price-based approaches that filter out demand for orbit space such that the most valuable satellites get suitable orbits allocated [43,44]. On the other hand, the benefits of science satellites or services for countries with different per capita wealth levels could be treated by a weighing scheme to make these benefits comparable, but the choice of the weighing system itself would need to be embedded in a discourse and open decision process. Another approach is to arrive at a commonly accepted set of allocation rules while accounting for the societal value of satellite basis services, equity effects of allocation, some minimum amount of new entrants and/or avoidance of market power, piloting innovations, etc., following the Institutional Analysis and Development (IAD) framework introduced by Ostrom et al. [40]. The IAD approach does include quantitative assessment but allows room for negotiation and consensus as well, largely meaning that at the expense of some degree of optimality, the actual feasibility and acceptability of the management scheme are improved.

Responding to the new demands, as determined by the economic theory mentioned earlier, would lead to decisions whether or not more spacecraft can be launched to a specific orbit that has a certain footprint. The admission of new launches can be handled through decision protocols, such as can be developed in the IAD approach. Queuing theory in space would mean that no more spacecraft can be launched to a specific orbit before some capacity on that orbit is freed, whereas freeing up orbit space can be addressed with technical removal initiatives. The interesting (and quite possibly the most difficult) decisions concern the determination of maximum capacity and how and when the orbital space can be incrementally occupied when the orbital capacity is reaching its maximum. In practice, it will be unlikely that the major space powers will adopt the concept of orbital capacity, especially if national security is at stake.

A recent article by Letizia et al. [48] also discusses the concept of orbital capacity with ample amount of figures and illustrations. They propose to use a debris index [49,50] as the measure for allocation of the orbital capacity and note that a register should be compiled, including log entries of upcoming missions by different operators. The log entry should also declare the reliability measure for the mission, serving to quantify the allocation of the capacity. Letizia et al. [48] envisage that the registration process could be carried out similarly as the ITU registration takes place, and the registry should be routinely updated to take into account the current situation of the targeted orbit. They also envisage a definition of a priority criterion in allocation of the orbits to prevent commercial missions from blocking scientific ones and call for equality between operators.

5.3. General principles

From the perspective of the economic theory, the key elements of managing the sustainable use of space are as follows:

1. Acknowledging the applicability of the economic sustainability principle and agreeing on its defining features (e.g. maximizing the number of properly functioning satellites per orbit, that is, the orbit capacity, over a larger timeframe);
2. Acknowledging the *external effects*[43] of space debris and agreeing on its defining features, such as the space debris generation capacity of satellites, and the effects of increments in volume and composition of space debris on the decrease in utilizable orbit space and the types of harm done to other satellites;
3. Operationalizing sustainable orbit space by quantifying the maximum allowable numbers of functioning satellites per period according to different technical property composites (lifetime, debris potential, etc.)
4. Operationalizing external effects, that is, assessing the costs of debris caused by orbital space limits and of collision damage with functioning satellites.

As regards governance of common-pool resources, the economics literature offers various examples such as the Montreal Protocol[44] on the global phasing out of ozone layer depleting substances as well as bottom-up designs proposed by Ostrom et al. [40] and Ostrom [41]. However, the first step, acknowledging the applicability of the sustainability principle and its defining features, is of paramount importance to get any kind of sustainable space management system in place. Such acknowledgment processes usually take considerable time. For example, the International Committee for the Protection of the Rhine,[45] involving policies with binding elements, was established in 1950, but effective policies only started to emerge in the 70s and even more so in the 80s of the previous century.

6. Concluding remarks

This article summarized the discussions at the First Sustainable Economy Workshop in January 2019, looking at the sustainable use of space from technological, legal, and economic perspectives. Two concepts, in particular, emerged in the discussion during the workshop, namely, *satellite sustainability footprint* and *orbit capacity*. These concepts, as noted, are already being developed by several actors. Work toward defining the concepts at an academic level in openly available peer-reviewed literature is a step forward in describing the situation on each orbit transparently and more accurately. An altogether different question is how to fit these concepts into the existing legal and regulatory framework, which would require agreement on how to manage orbital capacity, and its consequences in a transparent, trustworthy, and neutral manner. A third metric is also illustrated in this context, an aggregate global benefit that is obtainable from alternative satellite compositions resulting from different orbit allocation rules. It is unlikely that such

[43] That is, that space debris causes negative effects on other parties without compensating the affected parties.

[44] Practically, all countries in the world have ratified the Montreal Protocol on Substances that Deplete the Ozone Layer (effectively in force since 1989). The Treaty aims to get halogenated hydrocarbons (notably CFC's) replaced by other substances or other technologies altogether and is regarded as a successful treaty with a high degree of compliance. See https://ozone.unep.org/treaties/montreal-protocol.

[45] https://www.iksr.org/en/.

optimization procedure can be applied straightforwardly, both for political and legal reasons, aside from practical and conceptual uncertainties. Instead, a quantitatively supported negotiation process with commonly agreed criteria may be more likely to yield effects.

To further discuss the evolution of regimes pertaining to orbit utilization, it is relevant to evaluate the differences between regulatory (i.e. top-down) approaches and nonbinding, “self-organizing” (i.e. bottom-up) processes, both of which could contribute to furthering the sustainable use of space. A top-down process could mean an intergovernmental or national legislative approach aiming at developing a regulatory framework, including defined rights and obligations, limitations, supervision, and possibly enforcement and arbitrage. In contrast, a bottom-up, “self-organization” could be led by industry, technical experts, or standardization groups on a voluntary basis. Examples of such bottom-up processes are the ongoing process for on-orbit servicing standards and the Space Sustainability Rating by the World Economic Forum together with ESA and other actors. A caveat in the bottom-up approach is that the voluntary nature of its products requires independent, neutral, and transparent verification mechanisms which all parties trust, and thereby again, possibly, requiring top-down efforts. The rationale of both processes is driven by the need to provide practical solutions and, at the same time, the desire to generate certain benefits, whereby the ultimate motivation and rationale might differ depending on the process and its context.

In addition, an idea for a bottom-up approach based on sustainability market opportunities is also introduced in this context. It is not meant that markets should drive the sustainable use, rather that sustainable use enables new markets. The climate crisis has created a drive toward green energy and new market opportunities, for example, for wind and solar energy, which are both a market opportunity and a sustainability action. Similar opportunities could be envisaged around three space-related concepts: (1) mitigation of debris (e.g. preventing debris by deorbiting), (2) on-orbit servicing, and (3) active debris removal, which all contribute to, and support, sustainability. All three represent an economical opportunity: for example, a commercial upstream company may be interested in keeping its allocated orbit free of debris to safeguard its investment, creating a market opportunity for active debris removal. Furthermore, in-orbit servicing capabilities such as refueling will increase a satellite's lifetime, which can be reflected as savings, that is, the saving of a replacement spacecraft. Possible rules for clearing the orbit space after a mission creates a market opportunity for developing deorbiting devices.

In summary, this article conveys the discussions held at the First Sustainable Space Economy Workshop held on January 23–25, 2019, in Espoo, Finland. We note that more information sharing between different space actors is required to improve the long-term sustainability of orbital space. Discussions both at the top level and among grass-root level actors are needed. All in all, sustainable space is not a local or regional, but a global issue, calling for versatile *trans*disciplinary interactions. We intend to host such discussions in the future as a continuation to the successful first workshop.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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