IAC-19-A6.8.9

Space Sustainability Rating: Towards An Assessment Tool To Assuring The Long-Term Sustainability Of The Space Environment

Minoo Rathnasabapathy[a]*, Danielle Wood[a], Moriba Jah[b], Diane Howard[c], Carissa Christensen[d], Aschley Schiller[d], Francesca Letizia[e], Holger Krag[e], Stijn Lemmens[e], Nikolai Khlystov[f], Maksim Soshkin[f]

[a] *Space Enabled Research Group, Massachusetts Institute of Technology (MIT), United States*
[b] *The University of Texas at Austin, United States*
[c] *International Institute of Space Law (IISL), United States*
[d] *Bryce Space and Technology, United States*
[e] *European Space Agency (ESA), Germany*
[f] *World Economic Forum, United States*
[*] Corresponding Author: Email minoo@mit.edu

Abstract

The ever-increasing amount of space debris continues to pose a threat to valuable space assets. The reliance on space assets coupled with an expected growth of large constellations of micro-satellites and nano-satellites emphasize the critical need to foster responsible behaviour by all actors to ensure long-term sustainability of the space environment. The Space Sustainability Rating (SSR) was first conceptualized within the World Economic Forum Global Future Council on Space Technologies. The SSR aims to provide a new, innovative way of addressing the orbital challenge by encouraging responsible behaviour in space through increasing transparency of actors' debris mitigation efforts designed to support long-term sustainability of the space environment. This paper presents the work of an international and interdisciplinary team to contribute to the early definition of the technical element and operations of the SSR. The paper presents the SSR design methodology to provide a comprehensive rating for sustainability of space missions in the context of the general status of the environment and global level of adherence to space debris mitigation practices. The SSR would act as a voluntary mechanism, whereby actors undergo an evaluation of their mission through a questionnaire; existing indices and other information should be used in addition to a specific questionnaire in establishing a rating. By sharing its rating, the actor would provide a single point of reference externally for their mission, thereby increasing transparency and placing emphasis on its debris mitigation approach, without disclosing any mission-sensitive or proprietary information. The rating will act as a differentiator and trigger positive outcomes (e.g., impact insurance cost or funding conditions), incentivizing other actors to improve their behaviour. The design, development and implementation of the SSR requires a number of steps including the creation of a technological platform among the space actors to ensure awareness, promote positive concepts and guarantee transparency of the approach. Based on input from different stakeholders (eg. governments, regulators, space agencies, industry trade associations etc.), the paper proposes potential steps to design the technical metrics and parameters of the SSR. The paper further explores the feasibility of the SSR to positively impact elements of the Space value chain – from manufacturers and insurers to launch providers and operators, as well as end customers.

Keywords: Space Sustainability Rating, Space Debris, Space Environment, Long-term Space Sustainability

1. Introduction

1.1 Current status of the space environment

Ever since the start of the space age there has been more space debris in orbit than operational satellites. With a history of over 60 years of space activities, more than 5800 launches have resulted in 44000 tracked objects in orbit, of which greater than 20000 remain in space and are regularly tracked by the surveillance networks around the globe, including the US Space Surveillance Network, which covers objects larger than about 5-10 cm in Low Earth orbit (LEO) and 30 cm to 1 m at Geostationary orbit (GEO) altitudes. Approximately 26% of the catalogued objects are satellites of which only a small fraction, approximately 2000, are still operational satellites today [1]. Approximately 17% of the tracked objects are spent upper stages and mission-related objects such as launch adapters and lens covers. More than half of the population is made by fragments generated by more 520 break-ups occurred in space [2]. These fragmentation events are assumed to have generated a population of objects larger than 1 cm numbering on the order of 900000.

With the average annual launch rates observed in the last decade, and with future break-ups continuing to occur at average historic rates of 8 per year, the number of debris objects in space will steadily increase. As a consequence of the rising debris object count, the probability for catastrophic collisions will also grow progressively; doubling the number of objects will increase the collision risk by approximately four times. This self-sustained process, which is particularly critical for the LEO region, is known as the *Kessler syndrome* and it can be avoided by the timely application of mitigation and remediation measures on an international scale.

The application of such measures becomes even more pressing when we consider that the use of space has been changing rapidly. First, the number of payloads launched in LEO has reached now four times the level of ten years ago, with a steep increase in particular in the last two years. This growth in numbers is driven by the launch of small satellites, with around half of the satellites launched in the last two years having a mass smaller than 10 kg. Secondly, the proposed large constellations are also expected to contribute to the launch of an unprecedent number of satellites in LEO, whose impact on the sustainability of wider space activities is under evaluation [3].

1.2 International sustainability rating systems

Many countries and industries have introduced rating tools in order to improve the knowledge about the level of sustainability. The design of the Space Sustainability Rating (SSR) was based on existing global sustainability tools used in different industries. This section provides examples of sustainability rating tools used in other sectors that form the basis of the Space Sustainability Rating. Furthermore, it examines how rating tools have been developed over time, and seeks to provide insight into their successful global implementation.

Publicly displaying sustainable practices and credentials in the current 'sustainably-aware society' is a growing trend. The most well-known sustainability rating tool is the green building rating system in response to rising energy costs and growing environmental concerns. As the most important decisions regarding a building's sustainable features are made during the design and preconstruction stages [4], the aim of the rating system was to provide a framework for building owners, designers and operators to identify and implement practical and measurable green building design, construction, operation and maintenance solutions [4]. Evidence has shown that sustainable buildings are economically viable, resulting in a life cycle savings of more than ten times the upfront costs to support sustainable building design of approximately 2% [4].

Rating system, often within the same industry can vary depending on the country of region it is designed and implemented in. In the example of green buildings, sustainability rating tools act as a 'yardstick' to assess the environmental performance of a building. However, a number of different Green Building Rating System are used globally. The United Kingdom first introduced the Building Research Establishment Environmental Assessment Method (BREEAM) in 1990. The US Green Building Council launched the Leadership in Energy and Environmental Design (LEED) in 1998, used in the United States, Brazil, Canada and India. Australia and New Zealand follow the Green Star while Japan follows the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) and the Assessment Standard for Green Buildings (ASGB) in China.

While the rating systems might share common metrics, such as energy consumption, water efficiency, material use and indoor environmental quality [5], the ratings are constructed on different parameters and definitions. In most of the green building rating systems, the assessment is based on point-based system weighted in different criteria based on their importance as defined by the relevant rating system; LEED is an energy-oriented rating system while Green Star and ASGB balance various aspects of building sustainability [6]. While BREEAM and LEED required building to fulfill all prerequisites and minimum program requirements, other rating systems such as the German Sustainable Building Council (DGBN) do not define mandatory criteria [7]. Final environmental performance rating is determined by the sum of the weighted category scores. Recent studies [8-10] have been conducted on whether a certified project guided by one building rating tool can attain the same level under another green building rating system. It was noted that achieving the highest ranking in BREEAM ('Outstanding') was more difficult than achieving the highest ranking in other rating systems (Gold for DGBN; platinum for LEED) [7]. Differences in assessment schemes, criteria and weights, resulted in the achievement of the final scores, hindering a direct one-to-one comparison. Many rating tools have additionally been modified and adopted from earlier models to cater for local environmental, economic, social needs, as well as technology, government policies and standards that have evolved over the years.

2. Mechanisms to address space sustainability

2.1 International Coordination Bodies, Regulation and Norms of Behaviour

Early academic space debris research activities reached the international stage by the mid-1970s via conferences organised by the International Astronautical Federation. The effect whereby the generation of space debris via collisions and explosions in orbit could lead to an exponential increase in the number of artificial objects in space, in a chain reaction which would render spaceflight too hazardous to conduct, was first postulated by Donald Kessler in 1978 [11]. Exchanges between experts resulted in multi-lateral meetings and lead to the creation of the Inter-Agency Space Debris Coordination Committee (IADC) in 1993, founded by ESA (Europe), NASA (USA), NASDA (now JAXA, Japan), and RSA (now Roscosmos, Russian Federation). Nine more agencies have joined the IADC since: ASI (Italy), CNES (France), CNSA (China), CSA (Canada), DLR (Germany), KARI (South Korea), ISRO (India), NSAU (Ukraine), and UKSA (United Kingdom). The IADC was established as a forum for technical exchange and coordination on space debris matters, and can today be regarded as the leading international technical body in the field of space debris. Space debris has also been a recurring agenda item for the Scientific & Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space (UNCOPUOS) since 1994. A major step towards international cooperation for space sustainability was taken in 2002, when the IADC published the IADC Space Debris Mitigation Guidelines [12] and presented them to the UNCOPUOS Scientific & Technical Subcommittee. Based hereon, nations around the world have developed safety standards and specific guidelines but international standardisation of mitigation measures is the task of normative international standardization bodies such as the International Standards Organisation (ISO) [13].

In 2010, UNCOPUOS Scientific and Technical Subcommittee established the Working Group on the Long-Sustainability of Outer Space Activities. In June 2016, the Working Group developed a set of 12 voluntary guidelines that comprised of a compendium of internationally recognized measures and commitments towards the long-term sustainability of outer space activities. More recently, UNCOPUOS approved and adopted 21 Long Term Sustainability Guidelines under the agreement that the Working Group on the Long-Sustainability of Outer Space Activities within the UNCOPUOS Scientific and Technical Subcommittee continue discussions for five more years. While the guidelines are not legally binding under international law, States and international intergovernmental organizations are encouraged to "voluntarily take measures, through their own national or other applicable mechanisms, to ensure that the guidelines are implemented to the greatest extent feasible and practicable..." [14]. Operators of spacecraft, both commercial and governmental, already joint forces to mitigate collisions in congested regions by means of exchanging data such as within the Space Data Association. Moreover, a "coalition of the willing" has recently surfaced as the Space Safety Coalition: an ad hoc coalition of companies, organizations, and other government and industry stakeholders that actively promotes responsible space safety through the adoption of relevant international standards, guidelines and practices, and the development of more effective space safety guidelines and best practices [15].

A number of international coordination bodies continue to develop international norms of behavior in order to improve transparency in space and reduce the risk of misunderstandings and miscommunications among outer space actors. Some examples include; the United Nations International Code of Conduct against Ballistic Missile Proliferation, which seeks to increase efforts against the proliferation of ballistic missiles, the Hague Code of Conduct put forward by partners of the Missile Technology Control Regime (MTCR) to establish guidelines for States to exercising maximum possible restraint in the development, testing, and deployment of ballistic missiles, the United Nations Group of Governmental Experts (GGE) on Transparency and Confidence-Building Measures in Outer Space Activities which aims to improve transparency in space and reduce the risk of misunderstandings and miscommunications among outer space actors, and the European Union's International Code of Conduct for Outer Space Activities intended to enhance the security, safety and sustainability of all outer space activities by encouraging responsible behaviour in space by developing best-practice guidelines.

2.2 Technical Developments

2.2.1 Satellite Design

Some of the methods to reduce the risk of creating space debris are based on mission operators selecting physical design features of their satellite or specific orbit design strategies to reduce the time spent on orbit total, the time spent in heavily utilized orbits or to increase the ability of a satellite to respond to collision alerts. One team of analysts summarized that satellite operators tend to choose among an imperfect set of options for responding to the risk of space debris [16]. Some satellite operators choose to ignore the potential of an on-orbit collision during the design phase and only respond to warnings during the operational phase by adjusting their orbit, if they have that capability. Operators can take a more proactive approach in several ways. First, they can ask if their satellites will have the ability to avoid debris that threatens them; second, they can ask if they will do all in their power to reduce the likelihood that their satellite will become an uncontrolled piece of debris that threatens the satellites of others. In order to reduce the likelihood of an operable or inoperable satellite hitting their own satellite, operators can invest in different types of maneuverability with different levels of capability. Depending on the size of a satellite and the type of propulsion system it can support, the reaction time to adjust orbital parameters. Satellites that combine three axis control and a chemical propulsion system with ample fuel reserves are likely to have the widest range of operations to reach to potential debris. An electric propulsion system may provide maneuverability, with efficient use of fuel but with a longer time to achieve a given maneuver.

Many small satellites do not have agile attitude or orbit control systems; many have no propulsion system at all. Researchers seek proposals that can provide small satellites or lower-cost satellites with options to improve responsiveness to orbital debris collision warnings while maintaining a moderate cost and complexity. One example that is in development is the REGULUS propulsion platform that is proposed for CubeSats and uses gases such as Xenon with a Magnetically Enhanced Thruster within a 2Unit form factor [17]. The company called Busek is one of several vendors that provides propulsion systems for small satellites using hall effect, electrospray, monopropellant, electrothermal, ion and plasma thrusters. The lower thruster systems in their catalog only provide attitude control whereas their larger systems can be used for orbital adjustments [18]. In order to reduce the likelihood of a satellite creating become uncontrolled debris, fragmenting or threatening other satellites, operators have several choices. First, when they select their orbit, they can choose a location that is not crowded and they can consider a location that allows for an efficient path for deorbiting. One concept that is not yet used but has been examined theoretically is the idea of including a deployable solar sail within a satellite and using at the end of a mission to help a satellite harness solar radiation pressure to reduce the time spent on orbit as potential debris. One study simulated orbital profiles to achieve this in Low Earth Orbit, but further work is needed to produce operational solar sails before this can be widely adopted [19].

Satellite operators can decide during the design phase if they will adopt and follow the globally promulgated best practices for mission passivation, such as those referenced in the Debris Mitigation Guidelines of the IADC. Passivation measures including planning for steps to reduce the presence of stored energy in chemical, electrical or mechanical form during the post mission phase. Thus, satellite designers should plan for and execute steps to eliminate stored fuel, ensure that batteries are drained of stored power and ensure that electrical components cannot create faulty connections [20]. McKnight also notes that most satellite operators do not carry effective diagnostic sensors that could help operators determine whether spacecraft anomalies during a mission are due to impact from small pieces of space debris or due to other natural causes; thus, the wider space community would benefit from more on-orbit data collection about causes of spacecraft anomalies in order to validate theories about the likelihood of collisions with small, uncontrolled debris objects [21]. Beyond passivating the satellite, operators can choose to execute a post mission disposal strategy that fits their orbital regime. For Medium and Low Earth Orbit, this generally means executing a plan to reenter the satellite into earth's atmosphere, either by gradually lowering the altitude until drag causes reentry or by using a highly elliptical orbit [22] that eventually has a perigee within the boundary of earth's atmosphere.

As noted above, if a satellite has propulsion, it may be able to execute this orbital maneuver in a straightforward manner. However, satellites without propulsion or with limited fuel reserves need additional design approaches. There are many proposals for satellite operators with missions in low earth orbit to design a method to increase the drag of a satellite during the post mission disposal phase, such as inflating a sail, balloon or deploying fins that increase the drag, especially for missions in low earth orbit. Some on orbit demonstrations of such concepts have been performed, but there is not a widely accepted standard for designing drag-increasing features in satellites for post mission disposal [23]. Finally, note that operators can pursue design options to increase their effectiveness of tracking their satellites on orbit by using better orbital determination systems, placing visible items such as reflectors on their exteriors or buying high quality Global Navigation Satellite System receivers and accessing multiple ground tracking services to detect and identify their satellite.

2.2.2 Proposed Satellite Servicing

The risks caused by space debris are not only due to operational satellites, but also to discarded objects such a lens caps and rocket components. Some analysts divide potential collisions of space objects into categories such as a small, non-trackable orbital fragment striking an operational satellite, a medium sized trackable fragment hitting a large object that is not an operational satellite or two large derelict objects colliding and creating many new fragments. The goal to address the risks of large, unmanaged objects colliding with each other or with small pieces of debris, motivates exploration of active debris removal [23]. This may also be warranted if an operational satellite attempts post mission disposal and is unsuccessful.

Active debris removal is not yet being performed on a routine basis, but many ideas for the process have been proposed and on-orbit technology demonstrations are being prepared. One review explores a wide range of active debris removal concepts from using lasers, tethers, or using one satellite to actuate another as well as concepts harnessing sails, ion beam shepherding, and collection of materials [24]. Some analysts focus on identifying which targets are most likely to be helpful in reducing risk of space debris generation or collisions if they are removed [25]. Mission concepts for satellites that can approach non-operational satellites and move them into a deorbit trajectory or a safer location for long term storage have been proposed using solar sails [26], tethers [27] and hybrid chemical propulsion systems [28]. These concepts are generally at a low level of technology development and have not been demonstrated on orbit. Schaub et al note that active debris removal mission concepts are expensive, risky and unlikely to bring commercial return in the near term. One potential motivation to pursue them is that the capabilities used to have one satellite approach a non-cooperative piece of debris are similar to technical requirements for other potential space missions such as satellite servicing to extend life and resupply missions. NASA is pursuing several missions and long term research programs to enable satellite servicing. ESA is also pursuing a mission to demonstrate active debris removal. The startup company Astroscale plans to demonstrate and build a business case around active debris removal services, but they are still developing their technical capabilities.

2.2.3 Surveillance

When it comes to keeping track of objects of human origin in orbit, space situational awareness is largely based on what can be observed by means of ground based infrastructure. The work horse are space object catalogues, which are generated and maintained by space surveillance networks, that contain objects limited to larger sizes, typically greater than 10 cm in low-Earth orbits and greater than 0.3–1 m at geostationary orbits. The former is generally the domain of ground based radar system, which can detect even smaller sized object but not necessarily track them reliably enough to predict a next orbit. The latter is more the domain of ground based telescopes, which can exploit slower orbital velocities in higher orbits to have longer exposure times and hence high sensitivities. In both cases, the size sensitivity thresholds are essentially a compromise between system cost and performance. Once an object is reliably tracked and its orbit maintained in a space object catalogue, the quality of the orbit determination, i.e. the precision and prediction accuracy, can be further improved by tracking it with ground based laser systems. This is beneficial, for example, for collision avoidance actions of operational satellites encountering debris objects. The size regimes mentioned are sufficient to monitor nearly all intact spacecraft and launch vehicle orbital stages but not enough for the vast majority of space debris. Also new concepts, such as femtosats, are a challenge to be detected and tracked from ground. Space based sensors have been developed to improve the situation but are not suited for general cataloguing, and limited to detecting new objects and improving orbit knowledge on known objects. Recently, sensors used for space object cataloguing have also been used to derive attitude motions on object next to general positions. Knowledge of the meteoroid and space debris environment at sub-catalogue sizes is normally acquired through statistical analysis, e.g. by means of in situ impact detectors (detectors flying on spacecraft), which can sense objects down to a few micrometres.

2.2.4 Data Sharing

In the aftermath of the Iridium/Cosmos collision in 2009, the United States Strategic Command (USSTRATCOM) initiated its SSA Sharing Program. It provides no-cost SSA data and services that cover the whole mission of a satellite, from pre-launch preparation to end-of-life disposal, including conjunction assessments. The conjunction assessment process starts from collecting observations for the US Space Surveillance Network (SSN), which are processed to obtain the state of trackable objects in space; the trajectories of active satellites are screened against the catalog to identify potential conjunctions. The service is available to operators of active spacecraft, with two different levels (i.e. basic and advanced), depending on whether SSA Sharing Agreements have been signed with USSTRATCOM [29]. In both cases, the operators are notified in case of close approaches that meet some defined reporting criteria. In particular, Conjunction Data Messages (CDMs) are used to exchange spacecraft conjunction information and a standard for this message has been defined in order to enable consistent warning by different organizations [30].

Operators can support the USSTRATCOM activities by providing predictive ephemeris to cover, for example, planned maneuvers or to take into account active tracking of the satellite (and, thus, reduce the uncertainty on its state). Organizations, such as the Space Data Association, have specialized in providing screenings for operator-provided ephemeris, to reduce both on-orbit collision risk and radio-frequency interference. Historically, ephemeris have been exchanged through bilateral sharing between the operator and the SSA provider; nowadays, new trends of data sharing are emerging as multi-lateral sharing of the ephemeris not only with the SSA provider, but with other operators registered to the service or open publication of the ephemeris by the operator.

In addition, commercial entities are also entering in the SSA domain with the intention to offer an extended service with respect to the governmental one that, because of its connection with national security issues, cannot fully disclose the performance and the scheduling of the sensors used to track space objects. For this reason, initiatives such as the Open Architecture Data Repository, launched by the US Commerce Department, are emerging with the purpose of providing an infrastructure to exchange and validate SSA data from different sources, including commercial ones. The idea is to move from one government-owned database to a shared repository, which can be fed with products with different quality level, to be accessed by different users depending on their needs and applications.

2.2.5 Collision Coordination and Avoidance

Based on the warnings received by USSTRATCOM, or similar provider, an operator may decide to take action to mitigate the collision risk. Usually, this is done by performing a maneuver with a chemical propulsion system, some revolutions before the estimated Time of Close Approach (TCA). Other approaches are also possible such the use of low-thrust propulsion or differential drag to correct the orbit, which generally need a longer lead time to achieve the desired risk reduction.

As mentioned in the Introduction, operational satellites represent only a small fraction of the population in LEO, so most operators in this region perform collision avoidance maneuvers to avoid inactive objects. This is for example the case at ESA, where in 2018 a total of 28 collision avoidance maneuvers were performed and only two involved active satellites. Currently, contact details of the operators are exchanged through the SSA data provider, in the form of email addresses or phone numbers. Operators get in contact on a case-by-case basis to exchange information on the maneuverability status of the two objects and other relevant data. There is not a predefined right-of-way, but rather a common sense approach is adopted to decide which of the two satellites should maneuver, considering for example the available maneuver capabilities (e.g. availability of a propulsion system, ability to maneuver later, residual fuel) and the impact on operation (e.g. in the case where a station keeping maneuver is already planned and can be slightly modified to reduce the collision risk). Once more and more satellites are launched into LEO this model of interaction may not be viable any longer and a change in how collision avoidance processes are implemented may be required.

A first aspect is to promote data sharing, for example for what concerns the maneuverability of an object, its predicted ephemerides, its size, but also to make available points of contact in case of conjunctions. All these elements can contribute to improve the estimation of the collision probability and the design of an appropriate mitigation strategy. Secondly, besides the increase in the number of satellites, the improvement of SSA sensors may also contribute to an increase in the number of tracked objects and, therefore, in the collision warnings. This will push towards more automated operations for collision avoidance activities, with several on-going studies trying to assess which level of autonomy can be reached and to which extent ground control is needed for those operations. Finally, the adoption of different approaches for collision avoidance may also require more transparency from operators in sharing how reaction thresholds are defined, which time-line for decision is adopted and which operational availability is guaranteed (e.g. 24/7 staff available to react in case of collision warnings).

2.2.6 Space Traffic Management and Coordination

Beginning with the collision between the operational Iridum-33 and intact but abandoned Cosmos-2251 spacecraft in 2007 and latest with the advent of large constellation moving from paper studies into the launching of the prototypes, a new awareness has been instilled in space policy makers that the actions of a few impact the many. This gave rise to the notion of space traffic management or coordination. Various (international) think-tanks and national policy makers have attempted to fill the notion of space traffic coordination with content but the concrete idea is wide and far in between. On one hand, this can be limited to the discussion on which licenses an operator should obtain in order to be able to launch and operator under a national jurisdiction, whereas, on the other hand, it can go as far as defining rules of the road on which satellite has precedence to maneuver in case of a close approach between operational satellites. High level proposals have been made on international fora which aim to synthesize best practices without national objectives, e.g. [31], but both policy and technical obstacles remain to be resolved before a common understanding of the term can be reached. A practical thought example is the concept of launch collision avoidance practices. It is generally agreed that it is a good objective to avoid a collision when launching a new object into space; however, the positional uncertainty on the launch vehicle is so large that classical collision avoidance risk calculation effectively indicate a near 100% risk of colliding all of the time, and hence impede any launch. In practice thus, it become an operator by operator process to decide against what is screened, which safety zones to respect, and when to close a launch window. The most common is avoiding an intersection with the ISS orbit. The concept of safety or keep-out zone around objects can be taken further in the nascent industry of on-orbit servicing and associated rendezvous and proximity operations.

2.3 Role of NGOs and Academia

Over the past few decades, policymakers have sought to establish norms of behavior to enhance the safety and security of the space environment, taking into consideration the interests of all space actors. Non-governmental organisations (NGOs) such as Secure World Foundation and Space Generation Advisory Council contribute to all stages of the research cycle, often organise international fora bringing together international group of experts from the policy, academic, non-governmental and private sector space communities. The fora provide a neutral environment, allowing for open and constructive strategic discussion on key issues, priority setting, and knowledge translation to action. Additionally, these NGOs partner with universities and dedicated research agencies to support the generation, utilization and implementation of long term space sustainability norms of behaviour. Secure World Foundation and Space Generation Advisory Council currently hold permanent observer status at UNCOPUOS and occasionally provide updates to the UNCOPUOS Committees on their activities and research supporting space sustainability.

Jah [32] proposes that academia is poised to make significant contributions to Space Situational Awareness, and address key areas where other organisations lack the ability to comprehensively quantify and assess which countries are following space debris mitigation guidelines. Jah [32] describes five key areas in which academic institutions are positioned to contribute to space traffic management, orbital debris mitigation and the long term sustainability of the space environment. These include; (i) generating or aggregating scientific and knowledge through inquiry, rigor and resources to better address pressing challenges, (ii) the ability to question the current-state-of-practice in contrast to what is possible, (iii) pursue novel approaches through interdisciplinary and collaborative practices and disciplines, (iv) utilise the ‘neutral’ academic position to exchange data and technical idea that might not be otherwise possible due to national security and military considerations, and (v) develop a resilient future workforce that is exposed to many aspects of long term space sustainability.

3. Space Sustainability Rating

3.1 History of the development of the Space Sustainability Rating

The Space Sustainability Rating (SSR) was first conceptualized within the World Economic Forum’s Global Future Council on Space Technologies, a multi-stakeholder group of global experts that convene on a yearly basis to discuss broader sectoral challenges and opportunities. During the 2016-2018 term, the issue of orbital debris became the primary topic for the Council and a concept of *rating* the behaviour of different actors on orbit was born. The main idea was to create a voluntary mechanism to avoid the challenge of imposing anything on the community. Over the two year term, 2 physical workshops were organized involving not just Council members, but also invited guests who were experts in the domain. In the summer of 2018, following positive feedback on the concept, the World Economic Forum, at the request of the Council and key stakeholders, decided to create a formal project in order to build the rating. A request for proposals was issues in September of 2018 to select appropriate partners with technical and system expertise. Upon receiving a number of strong proposals for collaboration, the Advisory Committee for the SSR selected the proposals from ESA and MIT to lead the development of the SSR together with the Forum. The collaboration was publicly announced in May 2019. The current project partners represent a diverse and expert group that have the expertise as well as the networks to create a meaningful and impactful mechanism for the sector to drive sustainable behaviour as activity increases in Earth orbits.

3.2 Precursors to the Space Sustainability Rating

When analyzing the long term evolution of the debris population in case of different mitigation scenarios and launch traffic rates, one has to choose a metric to represent the status of the debris environment. The usual choice is to summarize these simulations in terms of the total number of objects or of catastrophic collisions. These metrics are effective in providing a single value to be used to be compare results, but they somehow hide some important differences. Consider for example the case when the population of objects contains 10000 active satellites or 10000 spent rocket bodies: the number of objects may be the same, but not the criticality of the space debris issue. In order to overcome these limitations, ESA began exploring different alternatives for the characterization of possible environment evolutions [33,34]. In addition, several authors started investigating possible metrics, usually indicated as *space debris indices*, to quantify the different impact of a spacecraft on the debris environment depending on its physical characteristics and orbital regime [35-40].

Most of the indices are essentially risk metrics with general expression

$$\text{Risk} = \text{Probability} \times \text{Severity} \qquad (1)$$

where the *Probability* term captures the likelihood that an object is involved in a fragmentation event and the *Severity* term quantifies the consequences of such an event on the environment or on other operators.

In particular, the formulation adopted for ESA's internal analysis, determines that the probability term captures the probability of collision with objects large enough to trigger a catastrophic collision (i.e. a collision where the object is completely fragmented) and the probability of explosion. The severity term quantifies the effect of such fragmentations by simulating the resulting debris cloud and propagating its evolution to obtain the resulting collision probability for operational satellites. This aspect, i.e. looking at the effects on operational satellites specifically instead of at the environment as a whole, is what differentiate this formulation from other available space debris indices. The reason for this choice is to switch from a generic *debris risk* to a more specific *collision risk*, which resonates more directly with operators [41]. In this sense, an object with a high index is characterized as one having a large impact on other operators' activities and push operators to act to reduce the numbers of such instances.

Equation (1), for which a detailed explanation of the computation approach can be found in [42], is not computed at a single epoch, but rather evaluated during the mission profile of an object to capture two key elements: the implementation of disposal strategies at the end of mission and the evolution of the environment in the time frame when the object is in orbit. In addition, factors such as the implementation of collision avoidance strategies are also taken into account in Equation (1). In this way, the resulting index can be used both as driver for design choices aiming at reducing the impact of a mission on the environment [43], but also as a metric to evaluate the adoption of mitigation strategies [44].

In practice, this can be done by computing the value of the index for all the objects in the environment and compare the obtained value with the one derived in a reference scenario. Such reference case can be built by introducing the concept of *Environmental Capacity* [45], which is the level of use of space (i.e. number of objects, orbital regions, adoptions of mitigation measures, etc.) compatible with a stable evolution of the environment. The value of the selected metric in the reference scenario can be compared to the one of the actual environment to understand how far the current environment is from the conditions for stable evolution. It can also be used to design a traffic management system where the available capacity (i.e. the total capacity minus the one already consumed by spent rocket bodies and inactive payloads still in space) is allocated across operators willing to launch new spacecraft, in a similar fashion to what already done by ITU for the frequency use.

3.3 Space Sustainability Rating Operation

It is expected that an effective SSR campaign will encourage all space operators (national, commercial, academic and non-profit) to have their satellite mission rated for space sustainability as part of the normal qualification and launch process. With this in mind, these space operators will consider sustainability design choices during each phase of the satellite lifecycle, design and materials selection, orbit selection, operations, and disposal.

The SSR would act as a voluntary mechanism, whereby actors undergo an evaluation of their mission through a questionnaire, sharing only high level information that is already required by the process of frequency allocation through ITU. Existing indices and other non-mission-sensitive or proprietary information will be used in addition to the questionnaire in order to establish a rating. By sharing its rating, the actor would provide a single point of reference externally for their mission, thereby increasing transparency and placing emphasis on its debris mitigation approach. In this way, the impact of future launch traffic can be assessed in advance and coordination mechanisms (e.g. promotion of mitigation measures) can be put forward, if needed.

In addition, such a registration process would not only enhance the transparency of process (e.g. by showing the predicted consumption of environmental capacity), but would also allow for direct positive feedback by highlighting well-performing missions.

To date, several options for the long-term administration and operation have been discussed. Due to the self-reporting nature of the SSR, it is anticipated that once established, the SSR would be handed over fully to an appropriate, trusted third party to integrate it into its activities and continue its evolution as a universally accepted industry resource tool. When considering a trusted third party to own, administer and operator the SSR, it is crucial to maintain impartiality. In addition, consideration should be given to developing and maintaining a mechanism for recording past ratings and data, prevention of duplication of efforts, confidentiality, and progress toward input into existing long-term space sustainability guidelines. In the long-term, the SSR can be made financially sustainable in two ways. First, commercial and national operators of spacecraft can pay for their rating (on a sliding scale that reduces the cost for low-income countries). Secondly, the organisation that hosts the SSR can also fundraise and produce a regular research-based product to provide educational experiences and reports about the state of space sustainability.

3.4 Comparison of the Space Sustainability Rating to 21 Space Sustainability Guidelines

As mentioned previously, UNCOPUOS has published a set of agreed guidelines, 21 out of 26 proposed, to create a framework for the long-term sustainability of outer space activities in 2018. They define the long-term sustainability of outer space activities as "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". There are clear parallels to be drawn between the gist of those guidelines and the objectives of the proposed SSR, but not all can included in an unambiguous manner. Table 1 below enables an overview of the similarities and differences in adoption between the SSR and the long term sustainability guidelines.

Table 1. Overview of SSR Adoption in relation to the Long Term Sustainability Guidelines

Long Term Sustainability Guideline	**Space Sustainability Rating adoption**
Policy and regulatory framework for space activities	
A.1 Adopt, revise and amend, as necessary, national regulatory frameworks for outer space activities	Not applicable as this is the domain of the nation States.
A.2 Consider a number of elements when developing, revising or amending, as necessary, national regulatory frameworks for outer space activities	Not directly applicable as this is the domain of the nation States. However, for the SSR, an operator and manufacturer can indicate which regulatory framework or standard is followed (if needed voluntary) which will influence the composite score.
A.3 Supervise national space activities	Not applicable as this is the domain of the nation States.
A.4 Ensure the equitable, rational and efficient use of the radio frequency spectrum and the various orbital regions used by satellites	Partially addressed, as the numerical risk indicator of the SSR functions as a proxy for the equitable, rational and efficient use of orbital regions vis a vis space debris. Radio frequency spectrum use is not addressed.
A.5 Enhance the practice of registering space objects	Captured as part of the composite indicator of the SSR.
Safety of space operations	
B.1 Provide updated contact information and share information on space objects and orbital events	Captured as part of the composite indicator of the SSR. The SSR itself would be an example of following the guideline.
B.2 Improve accuracy of orbital data on space objects and enhance the practice and utility of sharing orbital information on space objects	Captured as part of the composite indicator of the SSR.
B.3 Promote the collection, sharing and dissemination of space debris monitoring information	Not applicable to the individual operator or manufacturer targeted by the SSR.
B.4 Perform conjunction assessment during all orbital phases of controlled flight	Captured as part of the numerical risk indicator of the SSR.
B.5 Develop practical approaches for pre-launch conjunction assessment	Not captured, yet, as such procedures and their impact are still very much in

	development.
B.6 Share operational space weather data and forecasts	Not applicable to the individual operator or manufacturer targeted by the SSR.
B.7 Develop space weather models and tools and collect established practices on the mitigation of space weather effects	Not applicable to the individual operator or manufacturer targeted by the SSR.
B.8 Design and operation of space objects regardless of their physical and operational characteristics	Partially addresses as part of the composite indicator in terms of the design standard and regulatory framework followed. Whereas the spirit of the guideline is to avoid limiting certain consideration for certain classes of object, it needs to be pointed out that in the numerical risk indicator of the SSR, consideration is made for the space debris potential of an object which depends on the physical and operational characteristics.
B.9 Take measures to address risks associated with the uncontrolled re-entry of space objects	Not addressed as part of the SSR, which currently limits itself strictly to impact on outer space.
B.10 Observe measures of precaution when using sources of laser beams passing through outer space	Not addressed as part of the SSR, which currently limits itself strictly to impact on outer space.
International cooperation, capacity-building and awareness	
C.1 Promote and facilitate international cooperation in support of the long-term sustainability of outer space activities	Not applicable to the individual operator or manufacturer targeted by the SSR. However, the SSR itself would be an example of following the guideline.
C.2 Share experience related to the long-term sustainability of outer space activities and develop new procedures, as appropriate, for information exchange	Not applicable to the individual operator or manufacturer targeted by the SSR. However, the SSR itself would be an example of following the guideline.
C.3 Promote and support capacity-building	Not applicable as this is the domain of the nation States.
C.4 Raise awareness of space activities	Not applicable as this is the domain of the nation States.
Scientific and technical research and development	
D.1 Promote and support research into and the development of ways to support sustainable exploration and use of outer space	Not applicable as this is the domain of the nation States.
D.2 Investigate and consider new measures to manage the space debris population in the long term	Not applicable to the individual operator or manufacturer targeted by the SSR. However, the SSR itself would be an example of following the guideline.

4. *Conclusion*

To address the long-term sustainability of the space environment, efforts have been made by States, coordination bodies, and the United Nations to publish and build consensus on positive norms of behavior to avoid harm to the space environment, and ensure safety of space operations.

The work presented in the paper provides an overview of the definition of the technical elements, precursors, and operations of the SSR, and motivation to develop a comprehensive rating for sustainability of space missions in the context of the general status of the environment and global level of adherence to space debris mitigation practices. Rating systems are of great significance at international levels, and play an important role in 'speaking a common language' in order to progress toward achieving the long-term sustainable use of the space environment. Given the numerous definitions of 'sustainability' in the current space sector, and the lack of direct one-to-one comparison, the design of the SSR aims to consider the necessary steps needed to define, develop, implement and adapt a rating system such that it can be utilized by all actors in the space industry.

An overview of the current status of the space environment, population of human-made space debris, and expected changes to the space environment due to planned large-scale constellations are presented. In addition, a summary of the latest mechanisms to address space sustainability provides an overview of current-state-of-the-art technological developments and updates to space policy and regulation. The SSR aims to provide an innovative way of addressing the orbital challenge by encouraging responsible behaviour in space through increasing transparency of actors' debris mitigation efforts designed to support long-term sustainability of the space environment. Acting as a voluntary mechanism, the SSR allows actors to undergo an evaluation of their mission through a questionnaire;

existing indices and other information should be used in addition to a specific questionnaire in establishing a rating. By sharing its rating, the actor would provide a single point of reference externally for their mission, thereby increasing transparency and placing emphasis on its debris mitigation approach, without disclosing any mission-sensitive or proprietary information. With the recent publication of the agreed-upon 21 guidelines on long-term sustainability of outer space activities by UNCOPUOS, the SSR is expected to address these guidelines and complement them.

Further work is being developed to consider the definition, implementation and administration of the SSR. The design of the SSR is intended to be an iterative process via a series of collaborative workshops with stakeholders representing academia, industry and governments.

References

[1] Union of Concerned Scientist Satellite Database. https://www.ucsusa.org/nuclear weapons/space-weapons/satellite-database

[2] ESA Space Debris Office. ESA's Annual Space Environment Report, 2019. GEN-DB-LOG-00271-OPS-SD. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

[3] Virgili, B.B., Dolado, J.C., Lewis, H.G., Radtke, J., Krag, H., Revelin, B., Cazaux, C., Colombo, C., Crowther, R. and Metz, M., 2016. Risk to space sustainability from large constellations of satellites. *Acta Astronautica*, *126*, pp.154-162.

[4] Azhar, S., Carlton, W.A., Olsen, D. and Ahmad, I., 2011. Building information modeling for sustainable design and LEED® rating analysis. Automation in construction, 20(2), pp.217-224.

[5] Council, U.G.B., 2009. LEED–Leadership in energy and environmental design: green building rating systems. http://www. usgbc. org/leed/leed_main. asp.

[6] He, Y., Kvan, T., Liu, M. and Li, B., 2018. How green building rating systems affect designing green. Building and Environment, 133, pp.19-31.

[7] Hamedani, A.Z. and Huber, F., 2012. A comparative study of DGNB, LEED and BREEAM certificate systems in urban sustainability. The Sustainable City VII: Urban Regeneration and Sustainability, 1121.

[8] Nguyen, B.K. and Altan, H., 2011. Comparative review of five sustainable rating systems. Procedia Engineering, 21, pp.376-386.

[9] Sawadh, O., 2017. Sustainability and green building rating systems: LEED, BREEAM, GSAS and Estidama critical analysis. Journal of Building Engineering, 11, pp.25-29.

[10] Shan, M. and Hwang, B.G., 2018. Green building rating systems: Global reviews of practices and research efforts. Sustainable cities and society, 39, pp.172-180.

[11] Kessler, D.J. and Cour-Palais, B.G., 1978. Collision frequency of artificial satellites: The creation of a debris belt. *Journal of Geophysical Research: Space Physics*, *83*(A6), pp.2637-2646.

[12] Inter-Agency Space Debris Coordination Committee. Space Debris Mitigation Guidelines, 2002. http://www.unoosa.org/documents/pdf/spacelaw/sd/IADC_space_debris_mitigation_guidelines.pdf

[13] International Standards Organisation. Space Systems - Space Debris Mitigation, ISO TC 20/SC 14 N 24113, 2019. https://www.iso.org/standard/57239.html

[14] UNOOSA, Guidelines for the Long-term Sustainability of Outer Space Activities. A/AC.105/2018/CRP.20, 2018. http://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf

[15] Space Safety Coalition, Webpage, https://spacesafety.org/

[16] Schaub, H., Jasper, L.E., Anderson, P.V. and McKnight, D.S., 2015. Cost and risk assessment for spacecraft operation decisions caused by the space debris environment. *Acta Astronautica*, *113*, pp.66-79.

[17] Manente, M., Trezzolani, F., Magarotto, M., Fantino, E., Selmo, A., Bellomo, N., Toson, E. and Pavarin, D., 2019. REGULUS: A propulsion platform to boost small satellite missions. *Acta Astronautica*, *157*, pp.241-249.

[18] Busek Webpage, http://busek.com/technologies__cubesatprop.htm

[19] Schaus, V., Alessi, E.M., Schettino, G., Rossi, A. and Stoll, E., 2019. On the practical exploitation of perturbative effects in low Earth orbit for space debris

mitigation. *Advances in Space Research*, *63*(7), pp.1979-1991.

[20] Schaub, H., Jasper, L.E., Anderson, P.V. and McKnight, D.S., 2015. Cost and risk assessment for spacecraft operation decisions caused by the space debris environment. *Acta Astronautica*, *113*, pp.66-79.

[21] McKnight, D., 2017. Examination of spacecraft anomalies provides insight into complex space environment. *Acta Astronautica*.

[22] Armellin, R., San-Juan, J.F. and Lara, M., 2015. End-of-life disposal of high elliptical orbit missions: The case of INTEGRAL. *Advances in Space Research*, *56*(3), pp.479-493.

[23] McKnight, D.S., Di Pentino, F., Kaczmarek, A. and Dingman, P., 2013. System engineering analysis of derelict collision prevention options. *Acta Astronautica*, *89*, pp.248-253.

[24] Mark, C.P. and Kamath, S., 2019. Review of active space debris removal methods. *Space Policy*.

[25] Liou, J.C., 2011. An active debris removal parametric study for LEO environment remediation. *Advances in Space Research*, *47*(11), pp.1865-1876.

[26] Kelly, P. and Bevilacqua, R., 2019. An optimized analytical solution for geostationary debris removal using solar sails. *Acta Astronautica*.

[27] Jia, C., Meng, Z. and Huang, P., 2019. Attitude Control for Tethered Towing debris under Actuators and Dynamics Uncertainty. *Advances in Space Research*.

[28] DeLuca, L.T., Bernelli, F., Maggi, F., Tadini, P., Pardini, C., Anselmo, L., Grassi, M., Pavarin, D., Francesconi, A., Branz, F. and Chiesa, S., 2013. Active space debris removal by a hybrid propulsion module. *Acta Astronautica*, *91*, pp.20-33.

[29] 18th Space Control Squadron, Spaceflight Safety Handbook for satellite operators, 2019. https://www.space-track.org/documents/Spaceflight_Safety_Handbook_for_Operators.pdf

[30] CCSDS, Conjuction Data Message, 2013. https://public.ccsds.org/Pubs/508x0b1e2s.pdf

[31] International Academy of Astronautics, Cosmic Study on Space Traffic Management, 2006. https://iaaweb.org/iaa/Studies/spacetraffic.pdf

[32] Jah, M. K., Ten Eyck, B. C., ROOM Magazine Op-ed, Academia's role in space protection, space traffic management and orbital debris mitigation, 2016. https://room.eu.com/article/academias-role-in-space-protection-space-traffic-management--orbital-debris-mitigation

[33] Radtke, J., Flegel, S. K., Roth, S., & Krag, H. (2014). Deriving the spacecraft criticality from Monte-Carlo simulations of the space debris environment. In International Astronautical Congress.

[34] Rossi, A., Lewis, H. G., White, A. E., Anslemo, L., Pardini, C., & Krag, H. (2016). Analysis of the consequences of fragmentations in low and geostationary orbits. Advances in Space Research, 57(8), 1652–1663. https://doi.org/10.1016/j.asr.2015.05.035

[35] Yasaka T., Can we have an end to the debris issue?, in 62nd International Astronautical Congress, International Astronautical Federation, 2011. IAC-11-A6.5.1.

[36] Utzmann J., Oswald M., Stabroth S., Voigt P., Retat I., Ranking and characterization of heavy debris for active removal, in 63rd International Astronautical Congress, International Astronautical Federation, 2012. IAC-12-A6.2.8.

[37] Lewis H.G., ACCORD: Alignment of Capability and Capacity for the Objective of Reducing Debris, FP7 Final Report, University of Southampton, 2014. URL: http://cordis.europa.eu/docs/results/262/262824/final1-accordfinalreportsection4-1.pdf

[38] Rossi A., Valsecchi G.B., Alessi E.M., The Criticality of Spacecraft Index, Advances in Space Research, vol. 56, no. 3, pp. 449-460, 2015. doi: 10.1016/j.asr.2015.02.027.

[39] Anselmo, L. and Pardini, C., 2015. Compliance of the Italian satellites in low Earth orbit with the end-of-life disposal guidelines for Space Debris Mitigation and ranking of their long-term criticality for the environment. *Acta Astronautica*, *114*, pp.93-100.

[40] Letizia F., Colombo C., Lewis H.G., Krag H., Assessment of breakup severity on operational satellites, Advances in Space Research, vol. 58, no. 7, pp. 1255-1274, 2016. doi: 10.1016/j.asr.2016.05.036

[41] Letizia, F., Colombo, C., Lewis, H. G., & Krag, H. (2018). Development of a debris index. In Stardust Final

Conference, Astrophysics and Space Science Proceedings (Vol. 52, pp. 191–206). https://doi.org/10.1007/978-3-319-69956-1_12

[42] F. Letizia, C. Colombo, H. G. Lewis, and H. Krag. Extending the ECOB space debris index with fragmentation risk estimation. In 7th European Conference on Space Debris, 2017

[43] Letizia, F., Lemmens, S., & Krag, H., Environment capacity as an early mission design driver. In 70th International Astronautical Congress, 2019.

[44] Letizia, F., Lemmens, S., Virgili, B. B., & Krag, H. (2019). Application of a debris index for global evaluation of mitigation strategies. Acta Astronautica, 161(April), 348–362. https://doi.org/10.1016/j.actaastro.2019.05.003

[45] H. Krag, S. Lemmens, and F. Letizia. Space traffic management through the control of the space environment's capacity. In 1st IAA Conference on Space Situational Awareness, 2017