Journal of Environmental Management 349 (2024) 119382

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

# The cost of (Un)regulation: Shrinking Earth's orbits and the need for sustainable space governance

Darrell Martin-Lawson [a], Stefania Paladini [b,*], Krishnendu Saha [a], Erez Yerushalmi [a]

[a] BLSS-Birmingham City University, Birmingham, UK
[b] Faculty of Art, Social Sciences, Management, Queen Margaret University, Edinburgh, UK

A R T I C L E I N F O

Handling Editor: Jason Michael Evans

*Keywords:*
Space sustainability
Space debris
Areas beyond national jurisdiction
Active debris removal

A B S T R A C T

Outer space is infinite, useable planetary orbits are not. This makes the Earth's orbit a unique case of an Area Beyond National Jurisdiction (ABNJ) complex to address, difficult to use in a sustainable and equitable way and almost intractable to regulate at an international level. As of 2023, we remain far from attaining a sustainable orbital environment, and future uses of the Earth's orbits for new satellites constellations appear now increasingly at risk. Adopting a probability-based empirical model to project the growth trajectory of objects in space, this article argues that the sector will cross a 'critical density' threshold within the upcoming years unless strong remedial actions to clear up the orbits are implemented and estimates the potential costs of active debris removal measures. Our findings suggest that orbital sustainability is unlikely to come from technology alone, no matter how advanced or ground-breaking. A long-term solution will necessarily require a radical rewriting of the outdated, often conflicting international regulatory framework, which contributed to creating this debris crisis in the first place, shrinking the Earth's orbit to (almost) the point of no return.

## Credit author statement

This journal article is the product of the joint work of the four authors.

Darrell Martin-Lawson was the lead author and the main contributor to the model, the data collection and the analysis of the results. Stefania Paladini specifically contributed to the article design, the discussion of the regulatory framework, and the global space industry analysis. Krish Saha contributed to the literature review, the critical reading of the framework, and the revisions of the article. Erez Yerushalmi contributed in particular to the mathematical model of Section 3, the analysis of results in Section 4, and the critical reading and revisions of the article.

The four authors all agree to the article submission and publication.

## 1. Introduction

Transboundary resources, also referred as Areas Beyond National Jurisdiction (ABNJ), are prone to depletion risks and conflicts over access. This widely recognized phenomenon, known as the 'tragedy of the commons' (Hardin, 1968), is evident in various areas, including outer space and specifically in Earth's orbits, due to self-interested behaviours and lack of regulation or ownership mechanisms that hinder coordination, exacerbate conflicting interests, and impede the establishment and enforcement of transnational regulations.

The current legal framework governing outer space, which consists of the Five UN Treaties from the 1960s–1970s (Migaud, 2020), is increasingly inadequate and outdated, and Earth's orbits in particular face mounting challenges (Paladini, 2023). The rise of objects in space, such as satellites, space stations, and non-operational objects like space junk and debris, has increased rapidly due to the commercialisation of space and the expansion of private companies in the sector. Consequently, the probability of a cascading chain of collisions has increased, commonly known as a Kessler Syndrome (Kessler and Cour-Palais, 1978; Bastida-Virgili et al., 2016), and poses potential catastrophic environmental and economic consequences.

International agencies were the first to act, suggesting best practices, which, it is important to note, have no binding legal value. The Inter-Agency Space Debris Coordination Committee (IADC) recommended the implementation of end-of-life disposal measures for all LEO satellites, mandating their de-orbiting within a period of 25 years following their launch (Hakima and Emami, 2018); NASA has recently asked for a far shorter window of 5 years (NASA, 2022). GEO (Geosynchronous)

* Corresponding author.
*E-mail address:* spaladini@qmu.ac.uk (S. Paladini).

https://doi.org/10.1016/j.jenvman.2023.119382
Received 11 July 2023; Received in revised form 1 October 2023; Accepted 15 October 2023
Available online 10 November 2023

satellites are typically deorbited according to standard procedures and moved into a 'graveyard' orbit above the protected zone. Debris are closely monitored by national and international space agencies.

Initiatives, such as the one proposed by the Committee of Space Research's (COSPAR) to promote Planetary Protection Policies (PPP) are a good starting point (COSPAR, 2017), though insufficient since they do not address thorny legal issues (e.g., ownership of space junk and debris alike).

There is a growing literature on the need for defining, addressing, and ensuring sustainability in outer space (Dobos and Prazak, 2019; Ledkov and Aslanov, 2023; Li, 2023; Svotina and Cherkasova, 2023; Paladini et al., 2021) both in the sense of regulating human activities (ESA, 2022c; UN, 2013) and active debris removal. Strategies encompassing regulation of satellites disposal and debris mitigation have emerged as crucial means of managing the space debris environment (Usovik, 2023), with a few initiatives already trialled to actively attempt cleaning up the orbits (Astroscale, 2023; Biesbrok, 2015). However, although there are studies that estimates the likely growth of quantity of objects in space in terms of collision probability scenarios with the aim of costing its economic consequences and estimates the benefit of remediation initiatives (NASA, 2023a; OECD, 2020), there is still limited research that connects the growing threat of debris and international regulations –or the lack of—that allowed this to happen.

The aim of this paper, therefore, is to fill this conceptual gap and link between debris mitigation and regulation. We develop a forecasting model to estimate how imminent, and costly, the debris crisis will be without the implementation of sustainable space governance and provide some suggestions.

With this aim in mind, we first analyse (Section 2) the regulatory framework of outer space, from the original outer space treaties to recent, and controversial, national regulations (the USA's 2020 EO-Executive Order, 2020). We highlight the unique characteristics of the Earth's orbit(s) compared to other ABNJs, such as high seas and polar regions. We also discuss the current usage of Earth's orbits, showing the complexities of measuring and tracking space objects and the risks related to their rapid growth.

Section 3 discusses the methodological choices made for the design of our empirical model, offering the rationale behind our projected growth of the number of trackable objects and the choice of the probabilistic function, while Section 4 presents the results from the forecasting exercises and compares its findings to alternative models, discussing the level of minimum mitigation strategies required to attain a sustainable level of space activities growth. Section 5 attempts a cost benefit analysis and highlights that the real hurdle to mitigation measures is regulatory before than technological.

Section 6 takes stock of the article's findings, discusses limitations, and avenues of future research.

## 2. Earth's orbits as a unique example of Areas Beyond National Jurisdiction (ABNJ)

### *2.1. The regulatory framework of outer space*

Areas Beyond National Jurisdiction (ABNJ) are regions for which no nation has sole responsibility for management, and which have been, over the decades, the object of international treaties aimed at regulating the access to the transboundary resources they contain. Formal provision has generally been derived from the customary international law (Scovazzi, 2015, 2021; Von Rebay, 2023; Treves, 2005; Merkouris, 2020). Globalisation, the increasing complexity of economic activities, challenges from climate changes, and the call for sustainable growth are scrutinizing current regulatory frameworks Rose, 2000; Toth, 2017). In recent years, calls are made for a 'global legal pluralism' (Sentz and Ferson, 2002) that is better suited to face these challenges (Moore, 1973; Griffiths, 1986; Tamanaha, 2008; Somos, 2020).

The American Society of International Law includes listed under the ABNJ acronym four areas, and namely, Oceans, Polar Regions, Cyberspace, and Outer Space (ASIL, 2023). There are important communalities among them, which explains why they have been historically regarded as examples of 'global commons' (UN, 2013), starting from their regulatory framework set through international treaties.

The most well-known among them, and a reference for all the others, is the United Nations Convention on the Law of the Sea, which built on, and replaced, the four treaties of the 1958 Convention of the High Seas. In the same way, the polar regions are regulated by the Antarctic Treaty System, and outer space by the Outer Space Treaty (OST, 1967) and the other four treaties stemming from it.

The most important characteristics that ABNJ have in common is that they are all considered a shared heritage, or 'province of all mankind (e.g., Article (art) 1 OST; mirrored by art. 137 UNCLOS), which means they are not owned by any nation and must be used for the benefit of all and for peaceful purposes only (art 89 UNCLOS; art 2 OST). In the same way, they are recognized as global commons, open to all states and subject to specific legal regimes that govern their use. To ensure sustainable use and protection, this entails international cooperation and coordination to address common challenges.

Together with common characters, there are important distinctions among ABNJs, which is the reason why the current 'international space law' based on the Five UN Treaties of the 1960s–1970s and, particularly, the 1967 Outer Space Treaty (OST), developed on the customary laws of the high seas, have severe limitations. This is not, or not only, due to the overlapping areas of jurisdiction and the way national laws and existing treaties may clash in their provisions (Walton, 2017; Francioni, 2014; Francioni and Scovazzi, 1996; Hermida, 2004; Lucas-Rhimbassen, 2022). High seas, as much as outer space, are placed beyond the jurisdiction of any state, while the polar regions have limited sovereignty by certain states under specific treaties. Otherwise said, the clashes national-international regulations are a common and well-known problem for ABNJs.

What is uniquely problematic in the case of outer space is the fact that the existing regulatory framework makes no distinction in what comes under its remit. And, while there is no consensus about where space starts (the Karman line of 100 km above the sea level versus NASA's lower limit of about 52 miles), once we cross that invisible line, the 'outer space' regime applies, regardless of whether it is Lower-Earth Orbit (LEO), a celestial body, or deep space. This is a problematic generalisation because each of them is a very different environment with its own characteristics and peculiarities (Paladini and Castellucci, 2022).

Even more concerning is the recent surge in regulatory activities targeting outer space, primarily driven by economic motivations. One notable example is the Executive Order (EO) 13914 issued by President Donald Trump on April 6, 2020. The EO explicitly rejects the longstanding notion of outer space as a 'global commons' established by historical UN treaties. According to the EO, "*Outer space is a legally and physically unique domain of human activity, and the United States does not view it as a global commons,*" (EO 13914, 2020). While the measure solely applies at the national level and lacks international binding effects, it originates from the leading country in the space sector and sets a significant and noteworthy precedent. It removes the previously 'constraining concept' associated to the exploitation of 'global commons' (Cogolati and Wouters, 2018; Tepper, 2019; Goehring, 2020), along with any limitation previously implied by the UN Treaties. This situation presents a significant obstacle to achieving both equitable resource exploitation and a sustainable responsible growth.

Moreover, the Moon and other celestial bodies face similar challenges as those found in marine environment preservation zones (e.g., contamination avoidance and risks of resource depletion: Freestone, 2009; Costello et al., 2008; Fitzmaurice, 2017; Eisenbarth, 2022; von Rebay, 2023), offering valuable insights to draw upon. Earth's orbit, however, stands apart from these environments and offers little experiences thereby adding to the complexity of the situation. Furthermore, as we elaborate next and substantiate with our model, if prompt remedial actions are not taken, the orbit faces an imminent threat of excessive exploitation and could become unusable.

### 2.2. Earth's orbits and their threatened status

A good starting point to discuss 'space sustainability' is the United Nations' Committee on the Peaceful Uses of Outer Space (UN COPUOS) definition: *'the ability to maintain the conduct of space activities indefinitely into the future in a manner that realises 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*,' (UN COPUOS, 2018).

This statement highlights the specific challenges the Earth's Orbit - or orbits - present. If outer space is infinite, by definition, the space around Earth's orbit that can be occupied by satellites is not. The Earth's division in various orbits is internationally accepted, and the three most used by satellites are Lower Earth Orbit (LEO) - the closest to the planet, Medium Earth Orbit (MEO) and geosynchronous orbit (GEO; Iridium, 2018) as presented in Fig. 1.

Considering the number of objects sent to space, it is no surprise that overcrowding has quickly become an issue, with the ITU (International Telecommunication Union) issuing warnings about the overpopulation of GEO since the beginning of the 1970s (ITU, 1992). Monitoring has been historically challenging, and any discussion of sustainability in the Earth's orbits must consider two related but conceptually different issues: (i) the sheer number of objects sent into space and (ii) the consequences of their permanence creating further debris by collision.

A few international bodies track the number of objects sent to space, the European Space Agency (ESA) and United Nations Office for Outer Space Affairs (UNOOSA) among them. According to recent statistics (December 2022; European Space Agency, 2022) there were 14,450 objects sent to space in about 6300 successful rocket launches since 1957 (Sputnik 1 year), with more than 10,000 tonnes of materials. At the time of writing this article (July 2023), UNOOSA's Online Index of Objects Launched into Outer Space included 15,716 in their index (UNOOSA, 2023), the large majority of which in LEO. More importantly, this number includes 'space junk', i.e., satellites no longer functioning that still orbit the Earth, but not space debris, which are classified and tracked adopting different metrics, as explained in the next section. Fig. 2 gives a breakdown of the position of the space objects depending on their orbits and the timeline of their expansion.

This complicates the analysis and the development of mitigation measures aimed at addressing them because, for instance, the Inter-Agency Space Debris Coordination Committee (Kim, 2013) defines 'space debris' as non-functional man-made objects, including both space junk and satellites' fragments that are in the Earth's orbit. Differently from space junk, fragments are smaller pieces of the initial object that have broken up and are now orbiting at their trajectory without the ability to control them (Liou and Johnson, 2009).

The number of objects, excluding debris, is already high. But the future is even more worrying, a picture that is it not fully convey by the number of launches (Fig. 3) because of the change in the type of payload sent into orbit and the rate of growth. Fig. 3 shows that the number of satellites launched grew from 120 to 1807 between 2011 and 2022, 1273 of which were smallsat constellations, such as Starlink and OneWeb (BryceTech, 2022; Mathieu and Roser, 2022).[1] The constellations vary in type depending on their number and to the height of orbit. For example, by 1998, the Iridium Satellite network included 77 actives satellites (Maine et al., 1995).

Also alarming is the number of the newly proposed constellations, with projections indicating the launch of thousands of satellites that would increase traffic by more than fivefold in an already congested LEO (Polli et al., 2022). SpaceX's Starlink, the most advanced mega constellation project, currently includes over 2000 satellites in orbit, with Bernhard et al. (2023) estimating a total of 42,000 satellites once the constellation is completed. Other estimates give a smaller number for Starlink (29,988) but including also other operators - Astra (13,620), China SatNet (12,992), OneWeb (6,372) among them – the total number could read 76,606 (Tibor et al., 2022 as cited by NASA, 2023a).

This push for large satellite constellations in LEO amplifies the risk of collisions, consequently contributing to the increase of space debris that threaten the sustainability of the space environment (Bastida Virgili et al., 2016). To assess the danger posed by space debris and build a projection model, we first begin with an explanation on how they are formed and monitored.

## 3. Methods and data

### 3.1. Debris formation and monitoring

The most comprehensive and long-serving tracking system is the one provided by the Department of Defence US Space Surveillance Network (SSN) that includes "*launch detection and tracking, conjunction assessment and collision avoidance, human spaceflight* support*, manoeuvre detection, breakup identification, and re-entry assessment*" (Joint Task Force-Space Defense, 2022).

By December 2021, more than 27 thousand (k) orbital debris were tracked which had a size greater than 4 inches in diameter (10 cm, cm). These include non-functional spacecraft, abandoned launch vehicle stages, and fragmentation debris. But the number of debris is far greater, and according to NASA, there are about half a million (mln) fragments of 0.4 inches (1 cm) or larger, and approximately 100 mln around 0.04 inches (1 mm, mm) and larger (NASA, 2021)

ESA's focus is slightly different and centres around debris creation and fragmentation events, although its estimates are comparable to NASA's. They report that since 1957, more than 630 events had occurred due to explosions, collisions, or other unplanned events that have provoked fragmentation, listing close to 33.5k tracked orbital debris of 10 cm or greater, and around 130 mln untracked space debris of between 1 mm and 1 cm – defined as unidentified objects (UIs) (ESA, 2022b) These UIs are far more dangerous to existing satellites and space stations because they travel at very high speeds of up to 17,500 miles per hour (mph), and being untracked, collisions are very difficult to predict and subsequently perform collision avoidance manoeuvres.

In terms of severity as cause of debris formation, propulsion, breakup events of various kind (for instance, during take-off), collision, and Anti-satellite weapons (ASAT) testing have been to date the largest contributors, with collision-related cause deemed to grow in severity in parallel with the increase of the satellites launched into space (le May et al., 2018). Fig. 4 summarises the top 10 fragmentation events between 1957 and 2022.

In 2018 alone, there were eight instances of breakup events in LEO that resulted in more than 1000 (now tracked) large new debris (Fattakhov, 2019; Baranov et al., 2021). And, although there is a substantial literature discussing major hypervelocity (high-speed) collisions as critical causes of debris formation (Zhang et al., 2016; ESA, 2022b; Pardini and Anselmo, 2017; 2021), ASAT tests are the ones causing the most damage in terms of fragment produced, as the 2007 Chinese Fengyun 1C event, which was high enough to slow down natural orbital decay (Weeden et al., 2010).

Collisions yield severe consequences too, as exemplified by the well-known incident in 2009 when the Soviet derelict Cosmos 2251 (a typical example of space junk) collided with the operational satellite Iridium 33. Even after seven years, a debris cloud of 1453 trackable objects remains in orbit, accounting for a significant proportion of fragments at an

[1] A satellite constellation is generally defined as a group of satellites at a fixed orbit and distance from each other that have a single goal, be it navigational information or communication services (Abashidze et al., 2022; Wang and Li, 2023).

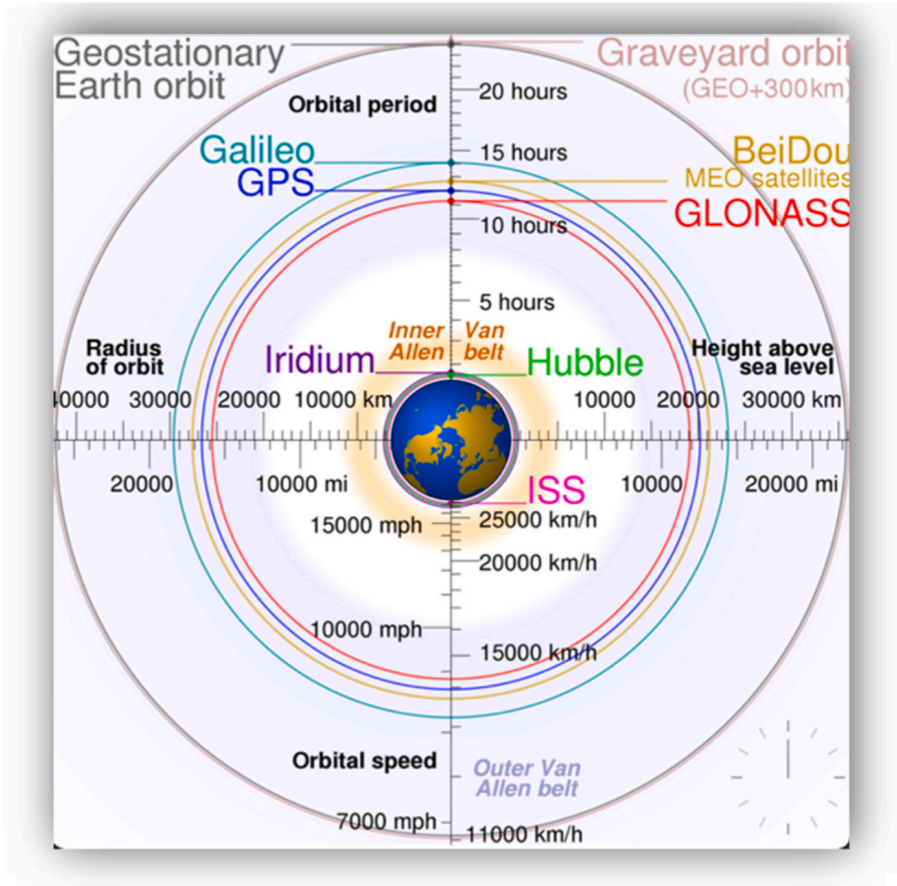


**Fig. 1.** The Earth's orbits.
(source: Creative Common, 2023)

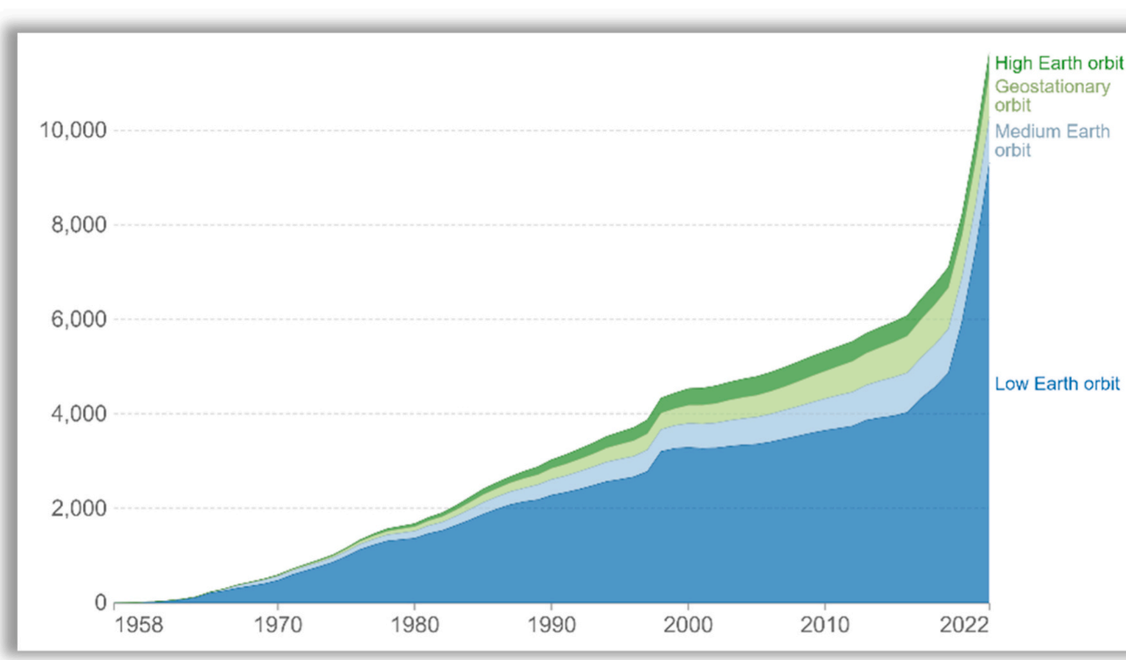


**Fig. 2.** Space Objects by Orbit (not including space debris).
(*Source: Our World In Data –MIT, CC-BY, 2023)*

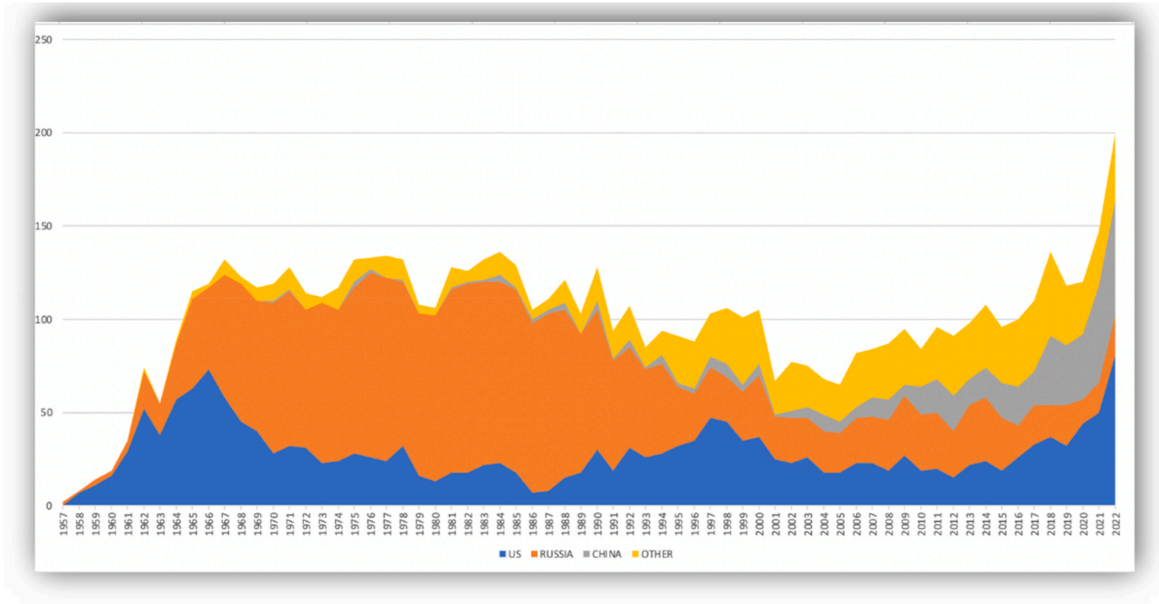


**Fig. 3.** Annual number of launches by country (1957–2022).
(Source: Authors' elaboration on US Space Surveillance Network dataset, 2023)

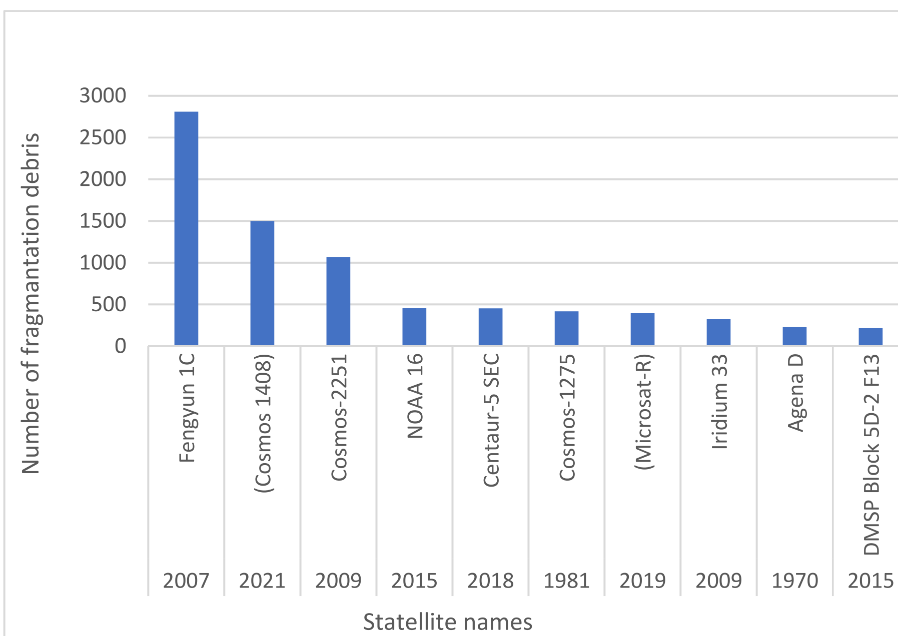


**Fig. 4.** Top 10 fragmentation events by number of fragments (1957–2022).
(Source: Elaboration on Paladini, 2023. Original data from ESA and JAXA data, 2022)

altitude of approximately 778 km. Notably, this altitude coincides with that of the Iridium constellation, and while no catastrophic collisions occurred between these fragments and the operational satellite constellation, it highlights the risks associated with a single collision in terms of potential long-term ramifications.

With plans for deploying additional mega-constellations, the likelihood of a hypervelocity collision increases. For example, on September 2, 2019, ESA was forced to execute a collision avoidance manoeuvre for its Aeolus satellite to avoid a potential collision with one of SpaceX's Starlink satellites. Space agencies send multiple collision risk alerts (Bernhard et al., 2023) with avoidance collision manoeuvres performed daily.

Le May et al. (2018) estimates the probability of a collision in LEO using 2018 SpaceX and OneWeb constellation data, adopting an empirical model based on Radtke et al. (2017) and ESA's MASTER software. They forecast *"a high probability for the occurrence of at least one collision for both the proposed OneWeb and SpaceX constellations during an operational phase of 5 years."* (Le May et al., 2018:15). The probability of at least one catastrophic collision for either OneWeb and Space X was estimated 5.0% and 45.8% respectively.

### 3.2. *The model*

To project the potential number of objects in orbit, we setup a model grounded in probabilistic economic theory (Ross, 2014). Orbital collisions are estimated drawing from models used in the transportation sector where a relationship exists between the number of unsafe events and their predictors. Different methods are used to model collision probabilities. For example, air traffic literature generally uses back-propagation neural networks (Liao et al., 2021; Chinatamby and Jewaratnam, 2023). Maritime transport is known to estimate and handle collision risks through an Automatic Identification System (AIS), which employs probabilistic methods to determine the future locations of ships (Sørensen et al., 2022), including deep neural network such as Bidirectional Long-Short-Term-Memory Mixture Density Network (BLSTM-MDN). The national highway in the UK adopts a non-homogeneous Poisson process to measure the occurrence of a collision, with the assumption that a collision does not influence the occurrence of another collision (Clements, 2021).

There are very few academic papers and reports that project the number of space objects and specifically debris and space junk. ESA (2023) use an inhouse generated tool called the Meteoroid and Space debris Terrestrial Environmental Reference (MASTER) to measure objects 0.0001 cm to 100m and uses 'sophisticated' mathematical techniques to predict the number of debris in the orbital environment. NASA (2023a), similarly to ESA, use the LEO-to-GEO Environmental Debris (LEGEND) Model to monitor and project the growth of debris in the orbital environment.

Academic studies such as Walker et al. (2000) project the average number of space objects larger than 1 cm using the Integrated Debris Evolution Suite (IDES) for the period of 2000–2050. It differs from our model in that they include five satellite constellations rather than a single orbit. Reynolds and Eichler (1995) used a mix of the Evolve and Chain models to estimate the number of debris from 1995 to 2090 in LEO. Neither studies, however, link the potential impact of mitigation measures on the orbital environment. In a related study, Bongers and Torres (2023) project the maximum number of satellites in space prior to a Keslar event. In our model, we focus on debris rather than satellites. We also draw upon two related theoretical papers: Maclay et al. (1996) that compares the Poisson and binomial distributions for modelling debris. They find that Poisson probability is a reasonable approximation of binomial distribution. Cament et al. (2021) used a mathematical Poisson labelled Multi-Bernoulli, multi-target tracking filter to predict the survival rate of space objects over time.

In our study, we develop an empirical accounting model to estimate the growth of trackable objects and subsequent debris from collisions. The model structure, overall, accounts for three main types of objects: currently tracked, new objects driven by technology, and additional satellites. As total objects rise, the probability of orbital collision rises - characterised by a Poisson distribution. Even though some objects decay into the atmosphere and removed, the net increase in objects is expected to increase the number of collision debris further and faster.

Our approach is similar to Clements (2021). However, Clements employs a disaggregated number of highways, while we have one "average" of all orbits. We do this to simplify the model and because this will not change our overall finding. Also, our assessment of the density parameter varies, and we discuss topics in line with others with emphasis on mitigating the shared space access domain (Grzelka and Wagner, 2019; Rao et al., 2020; Bernhard et al., 2023; Béal et al., 2020).

Our model is calibrated to ESA data, chosen their high level of reliability and timeliness, and relates to objects 10 cm or greater on average. We test three scenarios: low, base, and high, and have two model variants: commercialised (increased growth above business-as-usual) and an extension with small satellites (smallsats).

The total known objects in space $T_0$ is calibrated to the available data in Jan 2022, defined as $t = 0$. In period $t > 0$, the total objects in space $A_t$ is equal to the trackable objects $T_0$, with growth rate based on the past decade (i.e., a business-as-usual scenario). However, the projected growth in commercialisation activities and technological innovation in this sector, particularly in LEO, are expected to drive higher number of additional trackable objects $\Delta T_t$ (above the business-as-usual scenario). Moreover, $\Delta S_t$ specifically denotes the additional satellites that are anticipated to be launched due to commercialisation, which are not accounted for in $\Delta T$. Finally, all objects contribute to the accumulation of debris resulting from collisions, represented by $\Delta C_t$. We summarize the commercialised model below:

$$A_t = T_0\left(1 + g^T\right)^t + \Delta T_t + \Delta S_t + \Delta C_t \quad (1)$$

To pin-point the growth rate of trackable objects $g^T$, we assume it follows the economic growth rate of the space sector. We compute an Ordinary Least Squares (OLS) regression whereby the dependant variable is the log of the known trackable objects (from January 2011 to January 2022), and the independent variable is the log of global space economy (GSE). The Space Foundation (2021) estimates GSE in terms of a revenue-base valuation that includes all commercial revenue from space products, services, infrastructure, and support industries as well as the space budgets of US and Non-US governments. The coefficient retrieved is the elasticity between the average growth rate of GSE and trackable objects, $\epsilon^T = 1.3$ (with 95% confidence interval (CI): 1.5 to 1.0).

Next, we compute the business-as-usual growth rate of known trackable objects as $g^T = \epsilon^T \cdot G^T = 1.3 \cdot 5.0\% = 6.3\%$, whereby the average growth rate of GSE between 2011 and 2022 was $G = 5.0\%$. The growth rate due to commercialisation $g^{T_c} = \epsilon^T \cdot G^{T_c} = 1.3 \cdot 8.2\% = 10.3\%$ is obtained by using the commercialised projected GSE growth of $G^{T_c} = 8.2\%$ from Crane et al. (2020). Finally, $\Delta T = T_0[(1 + g^{T_c})^t - (1 + g^T)^t]$.

Similarly, we estimate the additional launched satellites that are due to commercialisation:

$$\Delta S = S_0\left[\left(1 + g^{S_c}\right)^t - \left(1 + g^S\right)^t\right] \quad (2)$$

whereby the business-as-usual growth rate $g^S = G^T \bullet \epsilon^S = 5.0\% \bullet 2.9 = 14.3\%$. The elasticity $\epsilon^S = 2.86$ (CI: 3.6 and 2.2) is computed by an OLS regression with log of satellites launched as the dependant variable and log of GSE as the independent variable. The same method is used to acquire the commercialised growth calibrated to $g^{S_c} = G^{T_c} \bullet \epsilon^S = 8.2\% \bullet 2.9 = 23.4\%$.

### 3.3. Collision debris

As total objects rise, the probability of a collision increases, given that the total volume of space (around Earth) remains fixed. To calculate the additional number of debris created by predicted collisions we estimated:

$$\Delta C_t = F \cdot P(k) \quad (3)$$

with $F = 2000$ being the average number of fragmentation debris generated by a collision (ESA, 2022a) and $P(k \geq 1)$ the probability of at least one collision $k$ per year.

We drew here from a few models in transportation, which use variants of the Poisson process to characterise different aspects of probabilistic models (Maclay et al., 1996; Clements, 2021; Cament et al., 2021). For simplicity, we omit the time-period $t$ and assume that collision probability follows a Poisson distribution $P(k) = \frac{\lambda^k e^{-\lambda}}{k!}$, with $\lambda = f(T)$ representing the mean number of collisions - a function of the number of trackable objects $T$ at each given period $t$.

We assume at least one collision per year

$$P(k \geq 1) = 1 - \frac{\lambda^k e^{-\lambda}}{k!} \quad (4)$$

and that the growth rate of the mean collusion per year $\lambda$ follows the growth rate of trackable objects per year

**Table 1**
Model parameters.

| Description | Parameter | Scenarios | | | Reference |
|---|---|---|---|---|---|
| | | Low | Base | High | |
| **Trackable Objects** | | | | | |
| Initial trackable objects | $T_0$ | 30, 024 | 30, 024 | 30, 024 | ESA (2022b) |
| Elasticity of tracked objects and economic activity | $\epsilon^T$ | 1.14 | 1.26 | 1.39 | OLS regression |
| Growth rate of economic activity | $G^T$ | 4.51% | 5.01% | 5.51% | Space Foundation (2022) |
| Commercialised growth rate of economic activity | $G^{T_c}$ | 7.35% | 8.17% | 8.98% | Crane et al. (2020) |
| Business-as-usual trackable objects growth rate | $g^T = G^T \bullet \epsilon^T$ | 5.11% | 6.33% | 7.67% | |
| Commercialised trackable objects growth rate | $g^{T_c} = G^{T_c} \bullet \epsilon^T$ | 8.37% | 10.33% | 12.5% | |
| **Collision Debris** | | | | | |
| Fragmentation parameter | $F$ | 1, 800 | 2, 000 | 2, 200 | ESA (2022a) |
| Average collisions per year | $\lambda_0$ | 0.12 | 0.13 | 0.15 | Aerospace (2021) |
| **Satellites Launched** | | | | | |
| Initial satellites launched | $S_0$ | 534 | 534 | 534 | Mathieu and Roser (2022) |
| Elasticity of satellites launched and tracked objects | $\epsilon^S$ | 2.57 | 2.86 | 3.14 | OLS regression |
| Business-as-usual growth rate of satellites launched | $g^S = G^T \bullet \epsilon^S$ | 11.61% | 14.33% | 17.34% | |
| Commercialised satellite launched growth rate | $g^{S_c} = G^{T_c} \bullet \epsilon^S$ | 18.92% | 23.36% | 28.27% | |

$$\lambda_{t+1} = \lambda_t \frac{T_{t+1}}{T_t} \tag{5}$$

Therefore, the collision probability $P(k)$ rises as more trackable objects enter space as follows.

For the Poisson distribution to hold for the orbital collision model, several assumptions were made, i.e., within any given year, collisions are independent, homogeneous, and asynchronous. The assumption of independence restricts the variability of probabilities, as collisions tend to enhance the likelihood of subsequent collisions in nearby regions, even within a short time frame. The assumption of homogeneity assumes a constant collision probability annually, disregarding potential fluctuations across different spatial regions, such as LEO, influenced by object density. Moreover, while simultaneous collisions are theoretically plausible, Aerospace (2021) estimates a frequency of approximately one significant collision every 7.5 years.

Table 1 provides a summary of the parameters used in the commercialised model. To assess the model's sensitivity, we include a high and low scenario at 10% around the baseline. In the results, we furthermore provide the 95% CI around the baseline.

## 4. Results

Fig. 5 shows the number of total objects projected in orbit, which includes operational satellites, non-operational satellites and debris. It shows that within 10 years the number of trackable objects will double in the baseline scenario and stresses the urgency for debris mitigation. The 95% confidence interval (CI) for the baseline shows that the high-rate scenario is also highly probable. This means that total trackable objects could reach about 115k, a 283% increase in 10 years due to the significant rise in predicted commercialisation of the space sector.

Fig. 6 shows the ten-year projected trend of satellite numbers in orbit. By the end of 2022, ESA (2022b) estimated a total of around 10, 550 satellites in space, of which 7900 of them classified as operational. Based on forecasts by Bongers and Torres (2023), a Kessler event would likely be triggered once the satellite count reaches approximately 72, 000. Our findings indicate that this critical threshold is projected to be reached around mid-2035, in the high scenario, or shortly before 2037, in the base scenario.

The commercialised projection model, so far, does not incorporate additional nanosatellites (such as Cubesats[2]) primarily because most of them operate in low and self-decaying orbits within LEO, and thus unlikely to generate substantial debris formation. However, the expected growth in deployment of smallsat constellations, such as Starlink, due to commercialisation, pose substantially higher risk of debris formation.

However, precise forecasting of the growth rate of smallsats is challenging due to the rapid and uncertain pace in technological advancements, as well as the ambiguity surrounding smallsat mitigation policies (Bastida Virgili et al., 2016). Relying solely on historical data cannot accurately reflect the potential additional rise in smallsats launches, defined as $\Delta SS$. These are in addition to those that have already been projected within the trackable objects $A_t$ in the commercialised projection. We thus extend the commercialised model in Eq (1) by

$$A_t^{'} = T_0 \left(1 + g^T\right)^t + \Delta C_t + \Delta S_t + \Delta SS_t \tag{6}$$

The same method used to calculate $\Delta S$ is then used to calculate

$$\Delta SS = SS_0 \left[ \left(1 + g^{SS_c}\right)^t - \left(1 + g^{SS}\right)^t \right] \tag{7}$$

with a growth rate $g^{SS} = G^T \bullet \epsilon^{SS}$. Using a log-log OLS regression with GSE as the independent variable, we compute the elasticity $\epsilon^{SS} = 6.5$ (CI: 8.2 and 4.8) and use the average growth rate of GSE $G^T = 5.0\%$. Thus, the business-as-usual growth rate is calibrated to $g^{SS} = 6.5 \cdot 5.0\% = 32.4\%$ and commercialised growth calibrated to $g^{SS_c} = 6.5 \cdot 8.2\% = 52.8\%$.

Table 2 provides a summary of the parameters used in the extended model.

When incorporating additional Smallsats, Fig. 7 reports that the projected number of objects could reach as high as 240k by 2033, in the baseline scenario.

[2] CubeSats –the most famous among the nanosatellite categories-are built to standard dimensions ("U") of 10 cm × 10 cm x 10 cm and assembled into 1U, 2U, 3U, or 6U, with weights in between 1 and 10 kg.

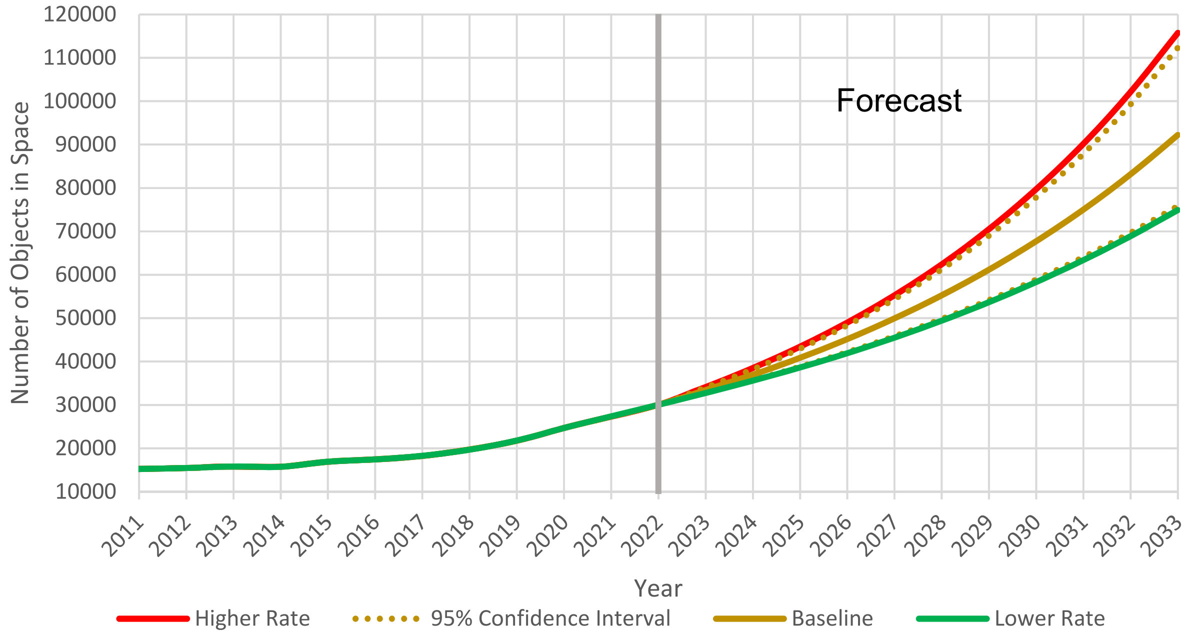


**Fig. 5.** The number of projected objects in space
The figure shows the total number of trackable objects $A_t$ over the next 10 years. In the base scenario, objects triple from 30k to around 90k trackable objects.

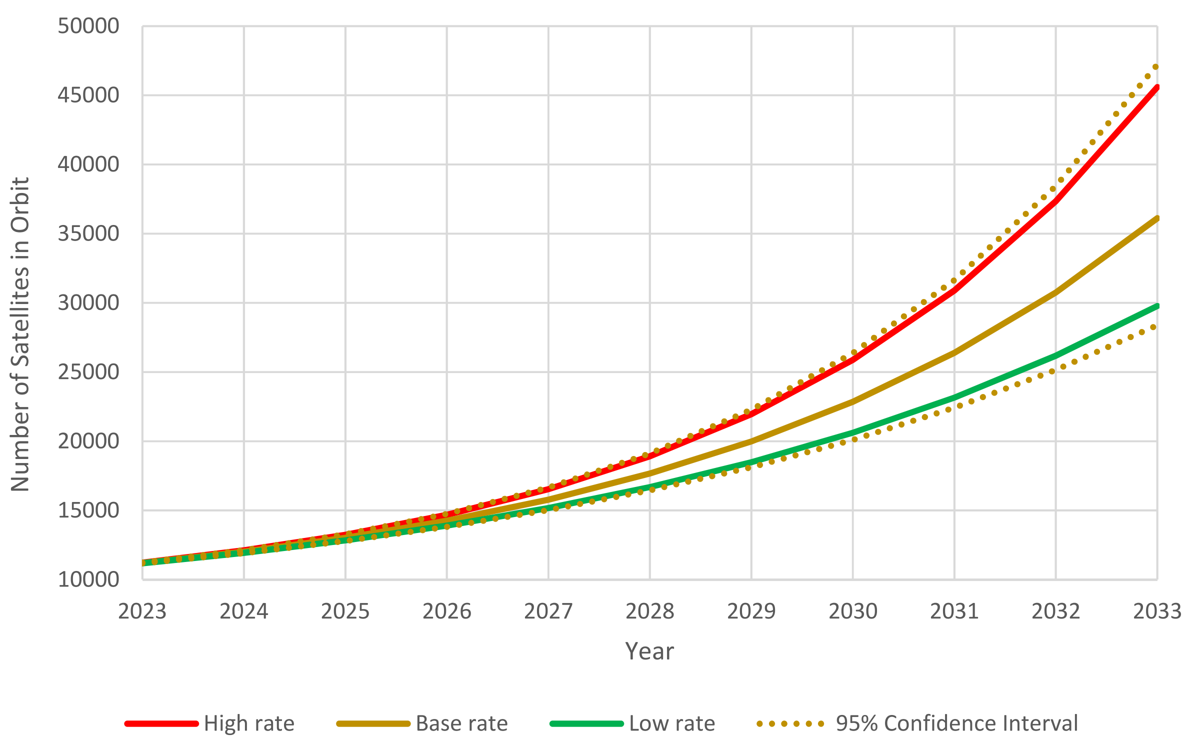


**Fig. 6.** The total number of satellites in space (all orbits)
This figure shows the total number of satellites in orbit over the next 10 years. In the base scenario, satellites triple from 10.5k to around 35k satellites. This exponential increase is due to the advancements in technology leading to predicted increases in commercial activity.

**Table 2**
Parameters for the extended model.

| *Description* | Parameter | *Scenarios* | | | Reference |
|---|---|---|---|---|---|
| Smallsats Launched | | | | | |
| Initial satellites launched | $SS_0$ | 1743 | 1743 | 1743 | BryceTech (2022) |
| Elasticity of satellites launched and tracked objects | $\epsilon^{SS}$ | 6.40 | 7.11 | 7.82 | OLS regression |
| Businss-as-usual growth rate of smallsats launched | $g^{SS} = G^T \bullet \epsilon^{SS}$ | 26.23% | 32.38% | 39.18% | |
| Commercialised growth rate of additional satellites launched | $g^{SS_c} = \mathrm{G}^{\mathrm{T}_c} \bullet \epsilon^{SS}$ | 42.75% | 52.78% | 42.75% | |

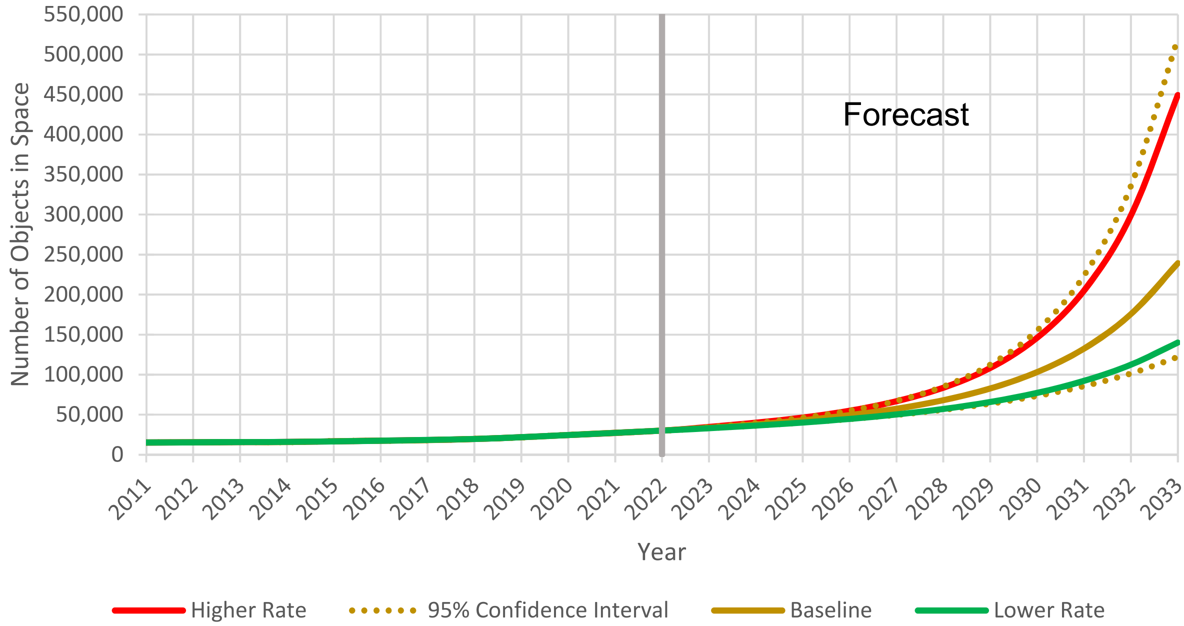


**Fig. 7.** Forecasted number of objects in space including smallsats (95% CI)
The figure shows the total number of trackable objects including smallsats over the next 10 years. This projection is, however, much less reliable because of the unknown trajectory of this sector in terms of the rapid technological advancements, use in LEO satellite communication, and near-future deployment.

### *4.1. Natural critical density*

A common aspect shared by both model variants (i.e., commercialised and smallsats) is the 'natural critical density". This is the rate at which collision-based fragments are naturally removed from space through atmospheric drag, pulling them into Earth's atmosphere where they are subsequently destroyed. If the debris population remains below this critical density, debris will eventually diminish when they re-enter the atmosphere and destroyed. However, if the population surpasses this critical density, and even after all space activities were ceased, the orbital population will continue to grow at a faster pace than atmospheric drag can eliminate objects, leading to exponential growth in

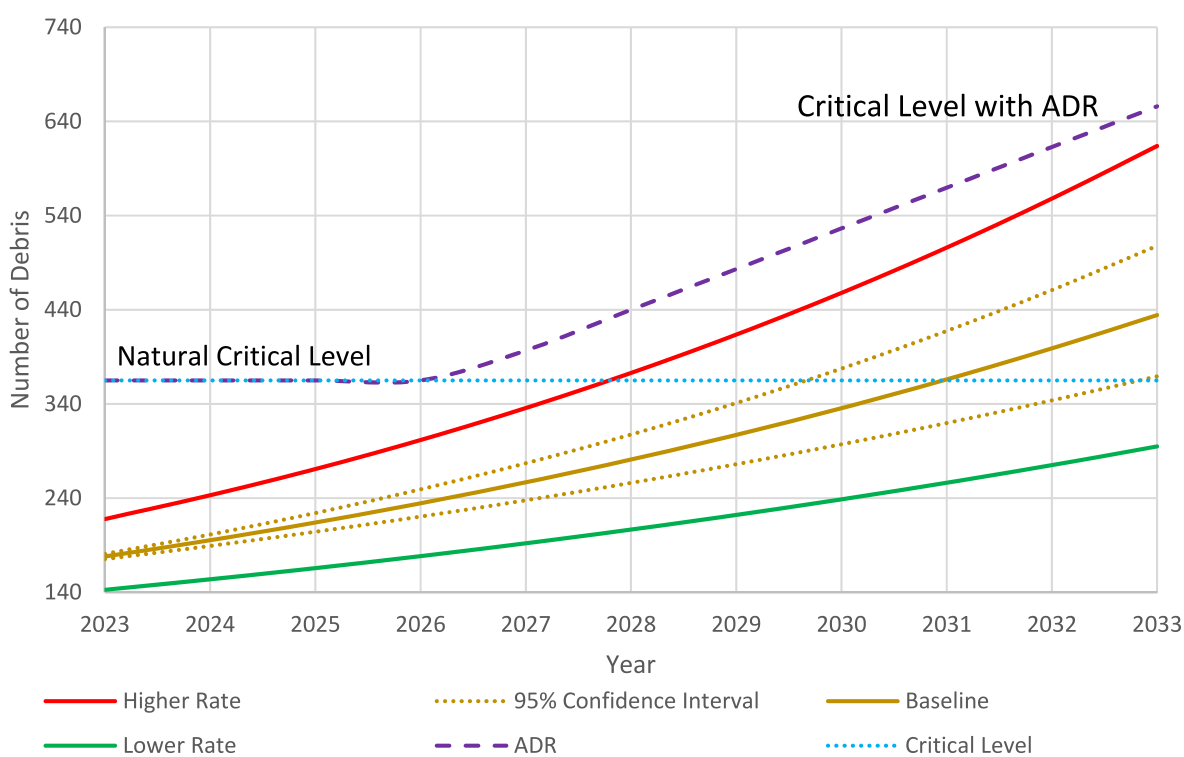


**Fig. 8.** Active collision-based fragmentation removal with re-entry (LEO)
The figure shows the additional number of collisions generated debris, per year, and the number of debris that clear naturally when re-entering the atmosphere (blue dotted line). Implement ADR strategy can delay the Kesler event. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

orbital debris - referred as a Kessler Event (Krisko et al., 2001). It is important to note that this phenomenon is particularly relevant to LEO, which is the most densely populated orbital region. Other orbits, such as GEO, exhibit different conditions in terms of satellite positioning and active mitigation measures, reducing the likelihood of such conditions.

The National Oceanic and Atmospheric Administration (2018) estimates that 200 to 400 objects re-enter the Earth's atmosphere yearly, equivalent to around an object per day (i.e., 365 per year), 60%–70% of which from LEO (ESA, 2023). Combining this information into our basic model (from Fig. 5), and assuming the proportion of objects in LEO is 65% (i.e., mid value), Fig. 8 shows the number of LEO collisions made objects given that all new space activities are halted. The blue dotted line depicts the critical level.

Based on our model, the number of collision-made objects will reach critical density by 2031 for the base scenario and by late-2027 in the high scenario – see Fig. 8. This gives a window of around 4–8 years to introduce debris mitigation and remediation solution, consistent with what the literature and industry studies report on this point.

Some estimate that a Kessler Event has already started because the definition of the critical density varies depending on which LEO altitude is being considered. In any case, left unchecked, space activity could be forced to a grinding halt because of the increase in collision probability (Krisko et al., 2001; Adushkin et al., 2020). The longer we wait for ADR technologies, however, the more costly they become, as discussed in the next section.

## 5. Discussion: debris remediation costs, mitigation measures, and the need for a global regulatory framework

Sustainability in space is under increasing scrutiny, starting from what it means in this specific context, given the multiple interpretations it receives in literature (Purvis et al., 2019). If we adopt, as we did in this study, the UN COPUOS definition applied to the specific context of debris mitigation, it will then entail the maintenance, renewal, or restoration of the item we want to make 'sustainable' (Wilkinson et al., 2001). If collisions can be predicted –and their consequences mitigated-through the adoption of accurate probabilistic methods, this would make the sector more sustainable by increasing safety and reducing the cost of damages.

There is no shortage of mitigation programmes, and, although the market size for the debris removal segment is currently difficult to estimate, some studies have suggested a value of USD 100 mln or more per year of activity (Zisk, 2022). ESA has, for instance, two ongoing programs: the *Clean Space Initiative* (set up in 2012 to address the problems related to both debris proliferation and crowded Earth's orbits), and the *Zero Debris approach* (launched in response to a scenario similar to the one we have modelled here, although based on different calculations; ESA, 2023).

There are at present no standardized methods or technologies for what is called Active Debris Removal (ADR) technologies. Some of them are at an advanced development stage, while others remain more experimental, and it is unclear when they will be fully operational (Bonnal et al., 2013). A few are under testing (Hakima and Emami, 2018), such as electromagnetic tethers (Hoyt, 2011), nets (ESA, 2014), iron beams (Bombardelli and Peláez, 2012), ground-based lasers (Phipps and Bonnal, 2016; Phipps, 2018; Shen et al., 2014; Fang et al., 2019) and the use of robotic arms (Flores-Abad et al., 2014; Hirzinger et al., 2012).

Market leaders in this field are Clearspace (2023) and Astroscale (2023). ClearSpace, the Swiss-based leader of in–orbit servicing created in 2018, secured approximately $28 mln in funding from ESA and other partners to launch in 2026 its first space debris removal mission *ClearSpace-1*. The UK-based Astroscale (2023) is another well-known presence into the ADR sector, with funding of around USD 376 mln and both the support of JAXA (Japanese Space Agency) and ESA. Both are good examples of the rising market value predicted for this sector but also the space agencies' growing awareness of the severity of the debris issue. Initiatives such as Net Zero Space (2023) or ELSA-D orbital removal mission (Astroscale, 2022) will likely become more frequent in the next coming years.

Assuming the first object could be removed in January 2026, our model projects the possibility to delay a Kessler Event depending on the level of ADR technology. For example, in Fig. 8, if ADR technology would rise by 10% per month (above the natural critical level), this would delay a Kessler syndrome event until approximately late 2041 (not shown in the figure) for the high rate. Implementing ADR soon could help achieve a sustainable orbital environment.

As previously discussed, we assumed that all future activity in space would halt, which is unlikely. Therefore, a much stronger ADR policy would need to be introduced to achieve a sustainable level of congestion in space. For example, targeting the high rate to achieve 10k objects in space[3] within a decade (i.e., 7 years after starting ADR in January 2026), we would need to remove 3500 debris in 2026, rising at a 30% per year. Cumulatively, this means that approximately 61k debris would need to be remove in the next decade. The Fig. 9 shows that the base and low scenarios could reach sustainability sooner because their debris growth is slower.

A crucial point for the implementation of active measures of debris remediation and removal is, of course, the cost. There are surprisingly very few studies (see e.g., OECD, 2020; NASA, 2023b) that address this specific point, probably related to the high level of industrial operational secrecy. A general estimate of debris-associated costs in GEO has been reported to hover around 5–10% of mission costs (OECD, 2020). Comparable estimates in LEO are unknown, but they are believed to be far higher than that.

NASA (2023b) has published in Spring (2023) a cost-benefit analysis of debris remediation, based on an extensive survey among satellite and spacecraft operators. In this report, there are two alternative cost/benefit scenarios of debris removal. The first computes the benefits associated with the removal of top 50 most concerning debris, citing McKnight et al. (2021) estimates at an overall USD 3.5 mln in the first year after removal, with a trade-off of several levels of costs depending on the various parameters (e.g., re-entry modalities). The second scenario considers the removal of 100k small fragments (1–10 cm) and provides far higher benefits (USD 23 mln in the first year).

NASA (2023b) also address the limits of the few existing cost-benefit studies on debris remediation, being either purely qualitative (Schaub et al., 2015), theoretical (Adilov et al., 2018), or unrealistic (Macauley, 2015) not without mentioning the weaknesses and constraints of their own model. The conclusion is that no-one (including satellite operators and space agencies) has a precise idea of the unit cost of debris and its remediation, a point also highlighted by the National Orbital Debris R&D Plan (National Science and Technology Council NSTC, 2021).

With these caveats in mind and acknowledging that this requires further research based on more extensive data, we attempted an initial cost-benefit estimate from debris removal in our model.

First, we calculated the annual total cost from debris impact at around USD 35 mln in 2023 and doubling to USD 66 mln by 2033, as the result of multiplying the total cost of replacing a satellite in LEO at around USD 253 mln (Vance and Mense, 2013) by the mean annual collision of $\lambda_t$ (from Eq. (5)). Second, we estimated that the number of LEO debris are around 12.5k in 2023 rising to 23.2k in 2033. This is obtained by multiplying the total trackable objects $A_t$ (see Fig. 5) by the proportion of LEO objects 65% and by their proportion of LEO debris 60% (ESA, 2023). Finally, by dividing the annual total cost by the

[3] There is no pre-determined appropriate level. 10k was chosen because it is a round number of objects – the level that existed in 2014.

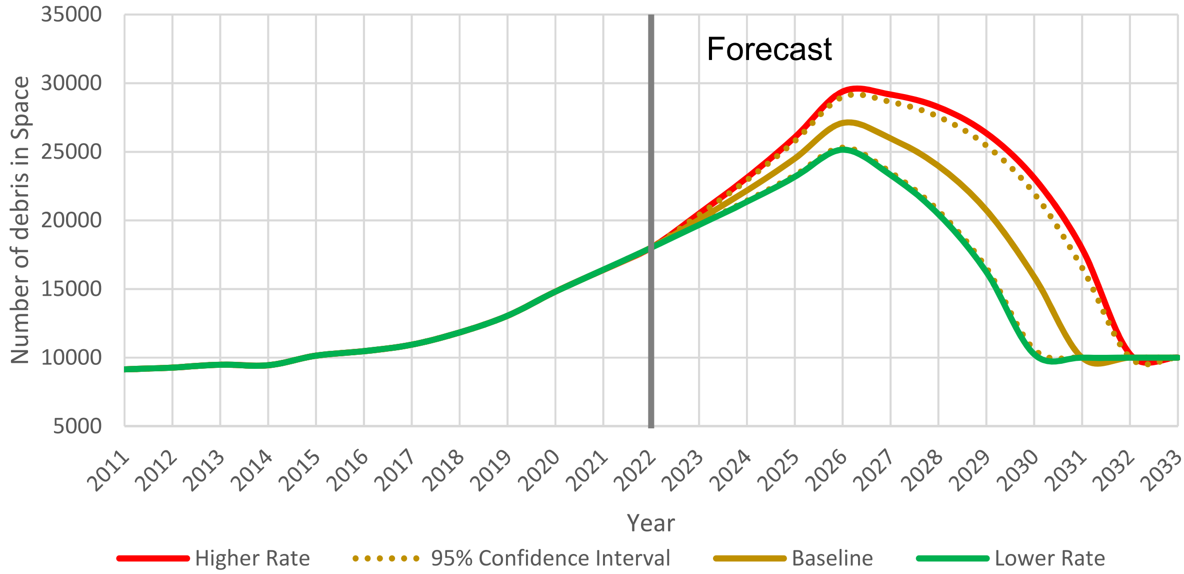


**Fig. 9.** The total amount of debris in space with ADR implementation from 2026
The figure shows the speed at which debris needs to be reduced by in for debris to be reduced to 10k within a decade by implementing ADR.

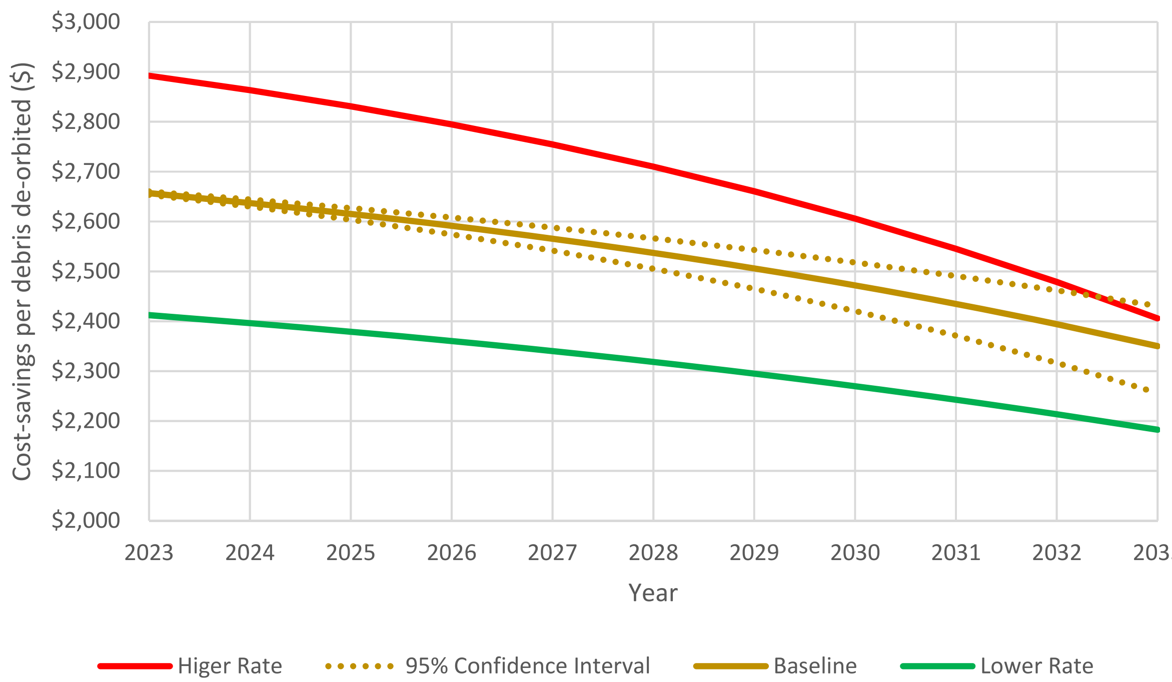


**Fig. 10.** Cost-savings per debris de-orbited (US $)
The figures shows that the cost-savings per debris de-orbited remains the same over time.

number of debris in LEO, we reach a cost-saving per *unit* of debris de-orbited of USD 2,657[4] in 2023, which falls to USD 2350 by 2033 (plotted in Fig. 10).

The fall in cost-savings happens because the total number of LEO debris rises faster than the number of LEO satellites launched to replace damaged ones (given that the total volume of LEO space is fixed). The longer ADR is delayed, the less cost-savings is achieved, a point all the studies reviewed here seem, unsurprisingly, to agree with.

However, progresses in space technology and ground-breaking ADR missions are only one side of the debris emergency solution. Underlying this discussion on the cost-benefit of the various technologies, there is the far more complex level of intervention that needs to be actioned to successfully address remediation and designing effective mitigation strategies. This level is not technical, but legal and (geo)political at the same time.

There is little doubt that addressing the debris crisis requires an international effort of coordination to modernise the existing regulatory framework of the space sector (Tronchetti, 2009). The lessons learned from the Cosmos 2251-Iridium 33 collision from 2009 and the protracted level dispute that followed is that the present regulatory framework (in that specific case, the UN Liability Convention of 1972) is

[4] A study for an ADR called Project Orion offered an estimate per unit varying in between USD 6000 to USD 300, depending on the power of the specific device used for debris removal (Phipps, 2010). This is overall consistent with our calculations.

not adapted to this 'new space age'. Because the responsibility for enacting space debris mitigation measures lies primarily with countries rather than private operators (Paladini, 2019; Listner, 2011; Kelso, 2012; Wang, 2010; Jakhu, 2010), private companies cannot even autonomously sue for eventual damages. Moreover, the ownership issue (the country that launches the space object retains ownership no matter its status; Baker, 1988; Christol, 1990) can, and already has, prevented any remediation at an international level (OECD, 2020) due to considerations of (i) risk of sovereign breach (Baker, 1988; Christol, 1990), (ii) residual value of the object although derelict (Perek, 2000, 2005), (iii) insurance claim, or even (iv) strategic considerations.

As in the case of other ABNJs, but in a fashion even more acute for the Earth's orbits, the international regulatory framework constitutes the beginning but also the eventual endpoint of many initiatives. Any serious attempt at a global intervention on active debris mitigation will require prioritizing and harmonising international space law, beginning with addressing the unique characteristics of Earth's orbits' and distinguishing its 'normative' jurisdiction form the broader domain of outer space. As discussed in Section 2, and worryingly in terms of the consequences for the entire sector, satellite market operators and national space agencies likewise, the steps taken by the USA through the 2020 EO, although primarily focused on the exploration and resource extraction of celestial bodies rather than specifically addressing Earth's orbit (Goehring, 2020), appear to lead us in a contrary direction, further complicating the establishment of an effective and sustainable framework for space governance.

## 6. Conclusions

The space sector matters.

Its total valuation has been constantly and steadily growing, reaching USD 469 bln in 2022, from USD 277 bln in 2011 (Space Foundation, 2022), thanks to the increase in private sector involvement, in what used to be a largely government-controlled environment. The satellite market represents the lion share.

But its important goes far beyond the numbers. What many fail to understand is that satellites are becoming crucial for what they contribute to the rest of the world economy and the civil society.

Their utilisation now spans over many sectors, and some of their services, such as Earth Observation to monitor natural and man-made phenomenon, have become crucial, from addressing climate changes and preventing natural disasters (Löw et al., 2021; Gao and Yuan, 2022; Telmer et al., 2006) to support agriculture and clean transition (Edwards et al., 2022; Hewson et al., 2020; Hill and Nassar, 2019):

The heightened level of attention given to the sustainability of the orbital environment is, therefore, of no surprise (Hakima and Emami, 2018; Usovik, 2023), considering the threat the debris crisis constitutes. NASA (2023a) warns that we may have already reached a critical point, particularly with the emergence of the proposed Starlink-like mega-constellations.

In this article, we contributed to the debate in two way, one empirical and the other theoretical.

Our empirical contribution to the discipline is a model that estimates the number of trackable objects and trackable debris objects based on the probability of collision. According to our estimates, within seven years, a Kessler Event is highly probable unless active mitigation measures (ADR) are introduced. We furthermore discussed the opportunity cost related to mitigation, a topic where research is still limited. Our model is calibrated to industry estimates, and it links the sector's economic growth as the main driver behind these projects. In this sense, the model differs from the others, which instead tend to focus on engineering parameters more than on economics. Our conclusions are in line with comparable studies and highlight the need for urgent action to address debris remediation. Further research on space debris is of the utmost importance, especially as it is technically still possible to delay a Kessler event by implementing ADR strategies.

Our model has a few limitations, some of which it shares with the existing literature and the prediction models discussed in Section 5. As it stands, the model provides a rough estimate because it only accounts for collision-based fragmentation and excludes ASAT tests, less frequent but far more damaging in terms of debris production. Furthermore, it only considers a single orbit, though different orbital altitudes have distinct critical densities (due to varying gravitational forces) and could lead to imbalances in population distribution and critical density levels. Limitations nonetheless, we believe the results are still valid, if anything because they might lead to underestimate, not overestimate the phenomenon. Otherwise said, things can only turn out worse, not better, and contributions in the kind of our study highlight the urgency of addressing the debris emergencies and highlight the dangers if no action is taken.

In terms of the theoretical contribution to the ongoing debate, this article identifies the root of the debris problem: outdated, overlapping, conflicting legal provisions no longer suitable for the current level of economic activity, and the overall lack of a regulatory framework specific to the Earth's orbits, affirming, instead of denying, their character of 'global commons' and their unique needs.

The centrality of this point cannot be stressed enough.

Unless this intractable conundrum is not addressed, maybe in a similar way of the upcoming High Sea Treaty (2023) adopted in June 2023 currently in ratification, it is unlikely substantial progress is made in time to avoid a Kessler event. As things stand now, the complexity around the orbits' transboundary status hinders achieving a sustainable usage of this resource. To make any international orbital management successful, the regulatory framework must legally allow for it first, starting with the establishment of a sustainable, equitable, internationally agreed space governance. There are no shortcuts.

## 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.

## Data availability

Data will be made available on request.

## References

Abashidze, A., Chernykh, I., Mednikova, M., 2022. Satellite constellations: international legal and technical aspects. Acta Astronaut. 196, 176–185. https://doi.org/10.1016/j.actaastro.2022.04.019.

Adilov, N., Alexander, P.J., Cunningham, B.M., 2018. An economic "Kessler Syndrome": A dynamic model of earth orbit debris. Economics Letters 166, 79–82.

Adushkin, V.V., Aksenov, O.Y., Veniaminov, S.S., Kozlov, S.I., Tyurenkova, V.V., 2020. The small orbital debris population and its impact on space activities and ecological safety. Acta Astronautica 176, 591–597.

Aerospace, 2021. Space Debris 101. Available at: https://aerospace.org/article/space-debris-101. (Accessed 11 May 2023).

Astroscale, 2022. Astroscale's ELSA-D Mission Successfully Completes Complex Rendezvous Operation Astroscale's ELSA-D Mission Successfully Completes Complex Rendezvous Operation. Available at: https://astroscale.com/astroscales-elsa-d-mission-successfully-completes-complex-rendezvous-operation/. (Accessed 22 September 2023).

Astroscale, 2023. Space Sustainability. Available at: https://astroscale.com/space-sustainability/. (Accessed 22 May 2023).

Baker, H.A., 1988. Liability for Damage Caused in Outer Space by Space Refuse. Annals of Air & Space Law 8, 183–227.

Anselmo, L., Pardini, C., 2017. An index for ranking active debris removal targets in LEO. In: 7th European Conference on Space Debris. ESA Space Debris Office, Darmstadt-ESOC, pp. 18–21.

ASIL, 2023. American Society of International Law Homepage at. https://www.asil.org/ (accessed on 1 August 2023).

Baranov, A.A., Grishko, D.A., Shcheglov, G.A., Sholmin, A.S., Stognii, M.V., Kamenev, N. D., 2021. Feasibility analysis of LEO and GEO large space debris de/re-orbiting taking into account launch mass of spacecraft-collector and its configuration layout. Advances in Space Research 67 (1), 371–383.

Bastida Virgili, B., Dolado, J.C., Lewis, H.G., et al., 2016. Risk to space sustainability from large constellations of satellites. Acta Astronaut. 126, 154–162. https://doi.org/10.1016/j.actaastro.2016.03.034.

Béal, S., Deschamps, M., Moulin, H., 2020. Taxing congestion of the space commons. Acta Astronaut. 177, 313–319. https://doi.org/10.1016/J.ACTAASTRO.2020.07.036.

Bernhard, P., Deschamps, M., Zaccour, G., 2023. Large satellite constellations and space debris: Exploratory analysis of strategic management of the space commons. Eur. J. Oper. Res. 304 (3), 1140–1157. https://doi.org/10.1016/j.ejor.2022.04.030.

Biesbrok, R., 2015. *Active debris removal in space: How to clean earth's environment for space debris*. CreateSpace, Charlestone.

Bombardelli, C., Peláez, J., 2012. Ion Beam Shepherd for Contactless Space Debris Removal 34 (3), 916–920. https://doi.org/10.2514/1.51832, 10.2514/1.51832.

Bongers, A., Torres, J.L., 2023. Orbital debris and the market for satellites. Ecol. Econ. 209, 107831 https://doi.org/10.1016/j.ecolecon.2023.107831.

Bonnal, C., Ruault, J.-M., Desjean, M.-C., 2013. Active debris removal: recent progress and current trends. Acta Astronaut. 85, 51–60. https://doi.org/10.1016/j.actaastro.2012.11.009.

BryceTech, 2022. Smallsats by the Numbers 2022. Available at: https://brycetech.com/reports/report-documents/Bryce_Smallsats_2022.pdf. (Accessed 21 December 2022).

Cament, L., Adams, M., Barrios, P., 2021. Space debris tracking with the Poisson labeled multi-Bernoulli filter. Sensors 21 (11), 3684. https://doi.org/10.3390/s21113684.

Chinatamby, P., Jewaratnam, J., 2023. A performance comparison study on PM2.5 prediction at industrial areas using different training algorithms of feedforward-backpropagation neural network (FBNN). Chemosphere 317, 137788. https://doi.org/10.1016/J.CHEMOSPHERE.2023.137788.

Christol, C.Q., 1990. Suggestions for Legal Measures and Instruments for Dealing with Debris. Environmental Aspects of Activities in Outer Space. State of the Law and Measures of Protection 13, 268–280.

Clearspace, 2023. A Mission to Make Space Sustainable. Available at: https://clearspace.today/. (Accessed 22 May 2023).

Clements, M., 2021. Statistical Methods for Comparing Road Traffic Collision and Casualty Rates: Proposed Approach. Guildford. Available at: https://nationalhighways.co.uk/media/a02hcmoc/statistical-methods-for-comparing-road-collision-and-casualty-rates-proposed-approach.pdf. (Accessed 6 March 2023).

Costello, C., Gaines, S.D., Lynham, J., 2008. Can catch shares prevent fisheries collapse? Science 321 (5896), 1678–1681.

Crane, K.W., Linck, E., Lal, B., et al., 2020. Projections of the Future Size of the Space Economy. Estimating the Value of Economic Activities in and for Space. Institute for Defense Analyses. Available at: http://www.jstor.org/stable/resrep25331.7.

Cogolati, S., Wouters, J. (Eds.), 2018. The Commons and a New Global Governance. Edward Elgar Publishing.

COSPAR, 2017. COSPAR's Planetary Protection Policy. https://cosparhq.cnes.fr/assets/uploads/2019/12/PPPolicyDecember-2017.pdf. (Accessed 21 July 2023).

Dobos, B., Prazak, J., 2019. To clear or to eliminate? Active debris removal systems as antisatellite weapons. Space Policy 47, 217–223.

Edwards, M.R., Holloway, T., Pierce, R.B., Blank, L., Broddle, M., Choi, E., Duncan, B.N., Esparza, Á., Falchetta, G., Fritz, M., Gibbs, H.K., 2022. Satellite data Applications for sustainable Energy transitions. Frontiers in Sustainability 3, 910924.

Executive Order (EO) 13914 Issued by President Donald Trump on April 6, 2020.

Eisenbarth, S., 2022. Do exports of renewable resources lead to resource depletion? Evidence from fisheries. Journal of Environmental Economics and Management 112, 102603.

EO 13914, 2020. Executive order. Encouraging international support for the recovery and use of space resources. Federal Register 85 (70), 6 April. https://www.federalregister.gov/.

ESA, 2014. How to Catch a Satellite. Available at: https://www.esa.int/Space_Safety/Clean_Space/How_to_catch_a_satellite. (Accessed 22 May 2023).

ESA, 2022a. About Space Debris. Available at: https://www.esa.int/Space_Safety/Space_Debris/About_space_debris. (Accessed 4 January 2023).

ESA, 2022b. Space Environment Statistics. Available at: https://sdup.esoc.esa.int/discosweb/statistics/. (Accessed 20 December 2022).

ESA, 2022c. ESA'S ANNUAL SPACE ENVIRONMENT REPORT. Darmstadt. Available at: https://sdup.esoc.esa.int/discosweb/statistics/. (Accessed 7 June 2022).

ESA, 2023. Analysis and Prediction. Available at: https://www.esa.int/Space_Safety/Space_Debris/Analysis_and_prediction. (Accessed 20 June 2023).

European Space Agency, 2022. ESA'S ANNUAL SPACE ENVIRONMENT REPORT. Darmstadt. Available at: https://sdup.esoc.esa.int/discosweb/statistics/. (Accessed 7 June 2022).

Fattakhov, R., 2019. Catalogue of space debris objects and Russian near-space monitoring system. In: All-Russian Conference "Space Debris Danger: Fundamental and Practical Aspects" 17-19 April 2019 [online] Moscow, Russia, p. 36. Available at: http://www.inasan.ru/wp-content/uploads/2019/04/Abstract-book.pdf [in Russian]. [Accessed 04 Jul. 2021].

Fang, Y., Pan, J., Luo, Y., Li, C., 2019. Effects of deorbit evolution on space-based pulse laser irradiating centimeter-scale space debris in LEO. Acta Astronautica 165, 184–190.

Fitzmaurice, M., 2017. International Convention for the Regulation of Whaling at. http://www.un.org/law/avl (accessed on 1 June 2022).

Flores-Abad, A., Ma, O., Pham, K., et al., 2014. A review of space robotics technologies for on-orbit servicing. Prog. Aero. Sci. 68, 1–26. https://doi.org/10.1016/J.PAEROSCI.2014.03.002.

Francioni, F., 2014. Revisiting sustainable development in light of general principles of international environmental law. In *Reflections on the Constitutionalisation of*. In: *International Economic Law*. Brill Nijhoff, pp. 473–492.

Francioni, F., Scovazzi, T. (Eds.), 1996. International law for Antarctica. Martinus Nijhoff Publishers.

Freestone, D., 2009. Modern Principles of High Seas Governance-The Legal Underpinnings. Envtl, 39. Pol'y & L, p. 44.

Gao, K., Yuan, Y., 2022. Is the sky of smart city bluer? Evidence from satellite monitoring data. J. Environ. Manag. 317, 115483.

Goehring, J.S., 2020. Why isn't outer space a global commons? J. Nat'l Sec. L. & Pol'y 11, 573.

Griffiths, J., 1986. What is Legal Pluralism? Legal Pluralism & Unofficial Law 1–24.

Grzelka, Z., Wagner, J., 2019. Managing satellite debris in low-earth orbit: Incentivizing Ex Ante satellite quality and Ex Post take-Back programs. Environ. Resour. Econ. 74 (1), 319–336. https://doi.org/10.1007/S10640-019-00320-3/FIGURES/1.

Hakima, H., Emami, M.R., 2018. Assessment of active methods for removal of LEO debris. Acta Astronaut. 144, 225–243. https://doi.org/10.1016/j.actaastro.2017.12.036.

Hermida, J., 2004. International space law. Legal Basis for A National Space Legislation.

Hardin, Garrett, 1968. The Tragedy of the Commons. Science 162 (3859), 1243–1248.

Hewson, R., Mshiu, E., Hecker, C., van der Werff, H., van Ruitenbeek, F., Alkema, D., van der Meer, F., 2020. The application of day and night time ASTER satellite imagery for geothermal and mineral mapping in East Africa. Int. J. Appl. Earth Obs. Geoinf. 85, 101991.

Hill, T., Nassar, R., 2019. Pixel size and revisit rate requirements for monitoring power plant $CO_2$ emissions from space. Remote Sens 11, 1608. https://doi.org/10.3390/rs11131608.

Hirzinger, G., Landzettel, K., Brunner, B., et al., 2012. DLR's robotics technologies for on-orbit servicing 18 (2), 139–174. https://doi.org/10.1163/156855304322758006, 10.1163/156855304322758006.

Hoyt, R.P., 2011. Propulsion and power harvesting performance of electrodynamic tethers. In: AIAA SPACE Conference and Exposition 2011. https://doi.org/10.2514/6.2011-7321.

Iridium, 2018. Satellites 101: LEO vs. GEO at. https://www.iridium.com/blog/satellites-101-leo-vs-geo (accessed on 1 August 2023).

Jakhu, R., 2010. Iridium-Cosmos Collision and Its Implications for Space Operations. In ESPI Yearbook on Space Policy. 2008/2009. In: Setting New Trends. Springer, Wien and New York, pp. 254–275.

Joint Task Force-Space Defense, 2022. Factsheet at. https://www.jtf-spacedefense.mil/About-Us/Fact-Sheets/Display/Article/3031729/joint-task-force-space-defense/ (accessed on 1 June 2023).

Kelso, T.S., 2012. ('Analysis of the Iridium 33-Cosmos 2251 Collision' Center for Space Standards and Innovation accessed 31 October 2021.

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

Kim, H.-D., 2013. IADC Key Definitions. Available at: https://www.iadc-home.org/documents_public/index/search_field/eNortjI2tlJy1CsuTcpKTS7RdtTLS8xNBVIlielAMjk_ryQ1r6RYyRpcMAypDUU~/search_keyword/eNortjI0tFJKSU3LzMssyczPK1ayBlwwPRIGZQ~~/page/1. (Accessed 20 December 2022).

Krisko, P.H., Opiela, J.N., Kessler, D.J., 2001. The critical density theory IN LEO as ANALYZED BY EVOLVE 4.0. In: Lacoste, H. (Ed.), 3rd European Conference on Space Debris. 2001. ESA. Available at: https://conference.sdo.esoc.esa.int/proceedings/sdc3/paper/96/SDC3-paper96.pdf. (Accessed 16 March 2023).

Ledkov, A.S., Aslanov, V.S., 2023. Active space debris removal by ion multi-beam shepherd spacecraft. Acta Astronaut. 205, 247–257. https://doi.org/10.1016/J.ACTAASTRO.2023.02.003.

Li, D., 2023. Upgrading space debris mitigation measures to cope with proliferating cyber threats to space activities. Adv. Space Res. 71 (10), 4185–4195. https://doi.org/10.1016/J.ASR.2022.12.055.

Liao, Y., Miao, Z., Yang, C., 2021. Probabilistic prediction of unsafe event in air traffic control Department based on the Improved backpropagation neural network. Math. Probl Eng. https://doi.org/10.1155/2021/9982723, 2021.

Liou, J.-C., Johnson, N.L., 2009. Characterization of the cataloged Fengyun-1C fragments and their long-term effect on the LEO environment. Adv. Space Res. 43 (9), 1407–1415. https://doi.org/10.1016/j.asr.2009.01.011.

Listner, M.J., 2011. The Moon Treaty: Failed International Law or Waiting in the Shadows? The Space Review.

Löw, F., Stieglitz, K., Diemar, O., 2021. Terrestrial oil spill mapping using satellite earth observation and machine learning: a case study in South Sudan. J. Environ. Manag. 298, 113424.

Lucas-Rhimbassen, M., 2022. The COST of Joining Legal Forces on a Celestial Body of Law and Beyond: Anticipating Future Clashes between Corpus Juris Spatialis, Lex Mercatoria, Antitrust and Ethics. Space Policy 59, 101445.

Macauley, M.K., 2015. The economics of space debris: Estimating the costs and benefits of debris mitigation. Acta Astronautica 115, 160–164.

Maclay, T.D., Fudge, M.L., Harris, C., 1996. In: Maclay, T.D., Allahdadi, F.A. (Eds.), Validity of the Poisson Distribution for Orbital Debris Impact Problems. https://doi.org/10.1117/12.256054, 31 October 1996. SPIE. pp. 116–126. doi:10.1117/12.256054.

Maine, K., Devieux, C., Swan, P., 1995. Overview of IRIDIUM satellite network. In: Proceedings of WESCON'95. 1995. IEEE, p. 483. https://doi.org/10.1109/WESCON.1995.485428.

le May, S., Gehly, S., Carter, B.A., et al., 2018. Space debris collision probability analysis for proposed global broadband constellations. Acta Astronaut. 151, 445–455. https://doi.org/10.1016/j.actaastro.2018.06.036.

Mathieu, E., Roser, M., 2022. Space Exploration and Satellites. Our World in Data. Available at: https://ourworldindata.org/space-exploration-satellites (Accessed 21 December 2022).

Merkouris, P., 2020. The Principle of Systemic Integration. P Merkouris,'The Principle of Systemic Integration'MPEiPro (2021) will be available here. http://www.mpi.lu/mpeipro/(Forthcoming). TRICI-Law Research Paper Series, (006).
Moore, S.F., 1973. 'Law and Social Change: The Semi-autonomous Social Field as an Appropriate Subject of Study', 7(4–719). Law & Society Review.
McKnight, D., Witner, R., Letizia, F., Lemmens, S., Anselmo, L., Pardini, C., Rossi, A., Kunstadter, C., Kawamoto, S., Aslanov, V., Perez, J.C.D., 2021. Identifying the 50 statistically-most-concerning derelict objects in LEO. Acta Astronautica 181, 282–291.
Migaud, M.R., 2020. Protecting Earth's orbital environment: policy tools for Combating space debris. Space Pol. 52, 101361 https://doi.org/10.1016/J.SPACEPOL.2020.101361.
NASA, 2021. Orbital Debris News at. https://sma.nasa.gov/sma-disciplines/orbital-debris (accessed on 1 June 2023).
NASA, 2023a. 3D/OD Evolutionary Mode. Available at: https://orbitaldebris.jsc.nasa.gov/modeling/legend.html. (Accessed 20 June 2023).
NASA, 2023b. Cost and Benefit Analysis of Orbital Debris Remediation. https://www.nasa.gov/offices/otps/home/index.html. (Accessed 31 August 2023).
National Oceanic and Atmospheric Administration, 2018. Does Space Junk Fall from the Sky? Available at: https://www.nesdis.noaa.gov/news/does-space-junk-fall-the-sky. (Accessed 16 March 2023).
National Science and Technology Council (NSTC), 2021. National Orbital Debris Research and Development Plan. https://trumpwhitehouse.archives.gov/wp-content/uploads/2021/01/National-Orbital-Debris-RD-Plan-2021.pdf (accessed on 31 August 2023).
Net Zero Space, 2023. Homepage available at: https://www.netzerospaceinitiative.org/. (Accessed 26 September 2023).
OECD, 2020. Space sustainability: the economics of space debris in perspective. OECD Science, Technology and Industry Policy Papers no., 87.
Paladini, S., Castellucci, I., 2022. Sovereign States, Private Actors, and (National) Space Laws. A Rapidly Evolving Landscape. In: Cocknell, C. (Ed.), Institutions of Extraterrestrial Freedom. Oxford University Press, Oxford.
Paladini, S., 2019. *The New Frontiers of Space. Economic Implications, Security Issues and Evolving Scenarios*. Macmillan, London.
Paladini, S., 2023. Unsustainable Wars? The Use of Weapons in Lower Earth Orbit. In: Caily, B. (Ed.), *Violence and Catastrophe in Uncertain Times*, Environmental Injustice and Catastrophe: How Global Insecurities Threaten the Future of Humanity, (Vol. 24).. Walter de Gruyter GmbH & Co KG.
Paladini, S., Saha, K., Pierron, X., 2021. Sustainable space for a sustainable Earth? Circular economy insights from the space sector. J. Environ. Manag. 289, 112511.
Pardini, C., Anselmo, L., 2021. Evaluating the impact of space activities in low earth orbit. Acta Astronautica 184, 11–22.
Perek, L., 2005, August. Management issues concerning space debris. In: Proceedings of the Fourth European Conference on Space Debris, Darmstadt.
Perek, L., 2000. Space debris at the united nations. Space Debris 2, 123–136.
Phipps, Claude., 2018. Laser Ablation Propulsion and Its Applications in Space. Chapter in Spriner Series in Materials Science. October 2018. https://www.researchgate.net/profile/Claude-Phipps/publication/328009206_Laser_Ablation_Propulsion_and_Its_Applications_in_Space/links/5f7cde48a6fdccfd7b4c8e73/Laser-Ablation-Propulsion-and-Its-Applications-in-Space.pdf. (Accessed 31 August 2023).
Phipps, C.R., Bonnal, C., 2016. A spaceborne, pulsed UV laser system for re-entering or nudging LEO debris, and re-orbiting GEO debris. Acta Astronautica 118, 224–236.
Polli, E.M., Gonzalo, J.L., Colombo, C., 2022. Analytical Model for Collision Probability Assessments with Large Satellite Constellations. Advances in Space Research. Available at: http://arxiv.org/abs/2205.15774. (Accessed 24 December 2022).
Purvis, B., Mao, Y., Robinson, D., 2019. Three pillars of sustainability: in search of conceptual origins. Sustain. Sci. 14 (3), 681–695. https://doi.org/10.1007/s11625-018-0627-5.
Radtke, J., Kebschull, C., Stoll, E., 2017. Interactions of the space debris environment with mega constellations—using the example of the OneWeb constellation. Acta Astronaut. 131, 55–68. https://doi.org/10.1016/J.ACTAASTRO.2016.11.021.
Rao, A., Burgess, M.G., Kaffine, D., 2020. Orbital-use fees could more than quadruple the value of the space industry. Proceedings of the National Academy of Sciences of the United States of America 117 (23), 12756–12762. https://doi.org/10.1073/PNAS.1921260117/SUPPL_FILE/PNAS.1921260117.SAPP.PDF.
Reynolds, R.C., Eichler, P., 1995. A comparison of debris environment projections using the evolve and chain models. Adv. Space Res. 16 (11), 127–135. https://doi.org/10.1016/0273-1177(95)98763-E.
Rose, F. (Ed.), 2000. Mercatoria: Essays on International commercial Law in Honour of Francis Reynolds. London: Routledge.
Ross, S., 2014. Introduction to probability theory. In: Introduction to Probability Models. Elsevier, pp. 1–19. https://doi.org/10.1016/B978-0-12-407948-9.00001-3.
Schaub, H., Jasper, L.E., Anderson, P.V., McKnight, D.S., 2015. Cost and risk assessment for spacecraft operation decisions caused by the space debris environment. Acta Astronautica 113, 66–79.
Scovazzi, T., 2015. The assumption that the United Nations Convention on the Law of the Sea is the legal framework for all activities taking place in the sea. *Ocean Sustainability in the Twenty-First*. In: *Century*. Cambridge University Press and UNESCO Publishing, Cambridge and, Paris, pp. 232–248.
Scovazzi, T., 2021. The Frontier in the Historical Development of the International Law of the Sea. In: *Frontiers in International Environmental Law: Oceans and Climate Challenges*. Brill Nijhoff, pp. 217–243.
Sentz, K., Ferson, S., 2002. Combination of Evidence in Dempster-Shafer Theory. Livermore. Available at: http://www.doe.gov/bridge. (Accessed 14 March 2023).
Shen, S., Jin, X., Hao, C., 2014. Cleaning space debris with a space-based laser system. Chinese Journal of Aeronautics 27 (4), 805–811.
Somos, M., 2020. In: Cavanagh, E. (Ed.), Empire and Legal Thought. Brill, Leiden, pp. 322–361.
Sørensen, K.A., Heiselberg, P., Heiselberg, H., 2022. Probabilistic maritime trajectory prediction in complex scenarios using deep learning. Sensors 22 (5), 2058.
Space Foundation, 2021. Annual Report 2021. Washington. Available at: https://www.spacefoundation.org/wp-content/uploads/2022/04/SpaceFoundation_2021-Annual-Report_Final-1.pdf. (Accessed 19 May 2023).
Space Foundation, 2022. Space Foundation Releases the Space Report 2022 Q2 Showing Growth of Global Space Economy - Space Foundation. Available at: https://www.spacefoundation.org/2022/07/27/the-space-report-2022-q2/. (Accessed 24 December 2022).
Svotina, V.V., Cherkasova, V., 2023. Space debris removal – review of technologies and techniques. Flexible or virtual connection between space debris and service spacecraft. Acta Astronaut. 204, 840–853. https://doi.org/10.1016/J.ACTAASTRO.2022.09.027.
Tamanaha, B., 2008. Sydney Law Review, pp. 375–430.
Telmer, K., Costa, M., Angélica, R.S., Araujo, E.S., Maurice, Y., 2006. The source and fate of sediment and mercury in the Tapajós River, Pará, Brazilian Amazon: ground-and space-based evidence. J. Environ. Manag. 81 (2), 101–113.
Tepper, E., 2019. Structuring the discourse on the exploitation of space resources: between economic and legal commons. Space Pol. 49, 101290.
Toth, O., 2017. The Lex Mercatoria in Theory and Practice. Oxford University Press, Oxford.
Treves, T., 2005. The International Law Commission's Articles on State Responsibility and the Settlement of Disputes. In: *International Responsibility Today*. Brill Nijhoff, pp. 223–234.
Tronchetti, F., 2009. The Exploitation of Natural Resources of the Moon and Other Celestial Bodies: A Proposal for a Legal Regime. Martinus Nijhoff Publishers, Leiden.
UN, 2013. UN System Task Team on the Post-2015 Un Development Agenda. https://www.un.org/en/development/desa/policy/untaskteam_undf/thinkpieces/24_thinkpiece_global_governance.pdf. (Accessed 4 July 2023).
Usovik, I.V., 2023. Review of perspective space debris mitigation solutions. Journal of Space Safety Engineering 10 (1), 55–58. https://doi.org/10.1016/j.jsse.2022.12.001.
Vance, L., Mense, A., 2013. Value analysis for orbital debris removal. Adv. Space Res. 52 (4), 685–695. https://doi.org/10.1016/j.asr.2013.04.024.
von Rebay, A., 2023. *The Designation of Marine Protected Areas: A Legal Obligation*. Springer Nature.
Walker, R., Stokes, P.H., Wilkinson, J.E., et al., 2000. Long-term collision risk prediction for low earth orbit satellite constellations. Acta Astronaut. 47 (2–9), 707–717. https://doi.org/10.1016/S0094-5765(00)00108-9.
Walton, B., 2017. Duties Owed: Low-Intensity Cyber Attacks and Liability for Transboundary Torts in International Law.
Wang, T., 2010. Analysis of Debris from the Collision of the Cosmos 2251 and the Iridium 33 Satellites. Science & Global Security 18, 87–118.
Weeden, B., Cefola, P., Sankaran, J., 2010. September. Global space situational awareness sensors. AMOS Conference.
Wilkinson, A., Hill, M., Gollan, P., 2001. The sustainability debate. Int. J. Oper. Prod. Manag. 21 (12), 1492–1502. https://doi.org/10.1108/01443570110410865/FULL/PDF.
Zhang, B., Wang, Z., Zhang, Y., 2016. An analytic method of space debris cloud evolution and its collision evaluation for constellation satellites. Adv. Space Res. 58 (6), 903–913. https://doi.org/10.1016/J.ASR.2016.03.016.
Rachael, Zisk, 2022. Exclusive: Euroconsult on Space Logistics Markets. Payload. May 18, 2022. https://payloadspace.com/exclusive-euroconsult-space-logistic-markets/ (accessed on 1 June 2023).