Pricing space junk: A policy assessment of space debris mitigation and remediation in the new space era

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Pricing space junk

A policy assessment of space debris mitigation and remediation in the new space era

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Executive summary

Decades of space exploration and exploitation have led to congestion in near-Earth orbital space. Though space debris is already a threat for operational spacecraft, the long-term danger is a cascade of collisions rendering some orbits unusable. Modeling of the space debris environment has shown that the tipping point of this cascading effect might already have been reached. The rapidly-growing space economy is bound to exacerbate this worrying situation.

The space debris issue is shaped by the physical characteristics of space, the economics of space exploitation, and the legal framework governing space. In this report, I address these three aspects and evaluate policy alternatives for space debris mitigation and remediation. I first conduct a thorough analysis of an ongoing reform of orbital debris mitigation rules for commercial satellites in the United States focused on a command-and-control approach. I then compare four policy instruments based on the market that could be applied in the space debris context: marketable permits, regulatory fees, liability insurance, and market-share liability and disposal payments.

Evaluating policy approaches requires data on their costs and benefits, which is largely lacking in the space debris context. The current economic impact of space debris is unknown, while the future economic impact is hard to predict. Three main reasons are identified for the cost data scarcity issue. First, damage due to untracked debris is unreported. Second, satellite operators are not transparent regarding the costs they face, e.g., for shielding, collision avoidance maneuvers, and post-mission disposal. Third, spending in Space Situational Awareness not only benefits space debris mitigation but also has military purposes. The future economic impact of space debris is even harder to predict due to the reliance on modeling, which requires strong assumptions, and due to the difficulty in estimating the total economic value we derive from near-Earth orbital space. However, there is no doubt that without action, the costs of space debris will rise significantly in the near future. Due to the slow clearing mechanism, debris accumulates in certain orbits. Space debris generated today can adversely affect space operations for many generations to come, way beyond the lifetime of the operators creating them.

Although scarce data prevents a comprehensive cost-benefit analysis from being conducted, the root causes of the congestion in near-Earth orbital space can be identified, and a suitable policy response devised. At the heart of the space debris issue is an incentive problem. Space users generate debris because they do not consider the cost they impose on others. A space user has minimal incentives to limit the creation of new debris as it bears all costs of its efforts, but the benefits are shared among all space actors. The same observation applies to the funding of remediation actions. Thus, an appropriate policy response must realign space operators' incentives and sustainability goals.

Space debris-related risks have two facets which call for different policy responses. The current debris-related risk results from past space activities and cannot be reduced by altering the space actors' incentives. Reducing this risk requires remediation and a mechanism to allocate its costs. Dealing with the historic debris population should probably rely on a state-centric approach, in the form of an international agreement to avoid free riding. Market share-disposal payments, which consist of apportioning the remediation costs proportionally with a state's current debris population, appear as an efficient approach.

Mitigating the debris-related risk resulting from future space activities requires a very different approach. In this case, the regulatory instrument must be able to incentivize actors to reduce their debris generation. Ex-ante requirements applied uniformly across operators with different compliance costs are inefficient and only partially align operators' incentives and space sustainability goals. Three market-based instruments can incentivize risk-reducing behaviors:

- *Liability insurance:* Through risk classification and premium pricing, insurance can act as a surrogate regulation. A well functioning liability insurance market could yield the necessary incentives and requires limited intervention from the regulator. However, the weak international liability framework for in-orbit activities coupled with the remote nature of space, which prevents damage investigation, greatly hamper this solution. As premium rates are priced commensurately with the risk of a claim and not the probability of a collision, the pricing mechanism of liability insurance premium rates currently cannot induce risk-reducing behaviors.

- *Marketable permits:* Tradeable licenses for the generation of a specific level of debris-related risk per time period could internalize the cost of debris generation. A cap-and-trade scheme is the most effective mechanism as it would limit the number of new debris created to a fixed amount. I have proposed a fungible unit of risk that would efficiently reduce debris creation. However, such a comprehensive unit of risk might be difficult to implement and increase the scheme complexity.

- *Regulatory fees:* Space users can be required to pay a regulatory fee for the generation of debris-related-risks. The unit of risk proposed for marketable permits could also be used in this scheme. Regulatory fees offer more certainty on the compliance cost and motivate long-term investments in mitigation. The most concrete example of this instrument is the recent proposal of a post-mission disposal bond by the Federal Communications Commission. Deposit and refund scheme would incentivize operators to reduce unplanned debris creation and post-mission disposal. However, requiring a sizeable ex-ante payment could be an obstacle to innovation and new space applications. To alleviate this problem, I propose to couple a deposit and refund scheme with a periodic fee.

Multilateral action would be preferred to avoid any debris-related risk leakage from a jurisdiction with higher requirements to jurisdictions with lower ones. However, I argue that, as a first step, unilateral action from the United States could be effective as the same requirements can be applied to entities requiring access to the American market. This mechanism can prevent operators from seeking a license in countries with less stringent regulations and could help drive change abroad.

Acknowledgments

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1 Introduction

Near-Earth orbital space faces a congestion problem. Since the dawn of the Space Age, at the end of the 1950s, thousands of satellites have been sent to orbit. This vantage point in microgravity is a valuable natural resource that is used, among others, for communication, Earth observation, and technology development. The conquest and exploitation of near-Earth orbital space have not been carried out with due care for the resource's sustainability. As a byproduct of space activities, space debris—non-functional human-made objects—has been generated. Pieces of debris exist in a wide variety of shapes and sizes. They include spacecraft lost or abandoned, objects released during normal operations such as rocket bodies or lens caps, and fragments resulting from collisions and explosions. While different processes lead to debris creation, only two mechanisms clear debris from orbits: atmospheric drag and direct retrieval. The residual atmosphere drags objects down, but this process can take from a few days to millions of years, depending on the initial altitude of the object and its ability to overcome drag. Uncrewed direct retrieval of debris has not been performed yet, but a technical demonstration of the technologies necessary for retrieval should launch this year, and a first mission to remove a piece of debris has recently been funded by the European Space Agency and should launch in 2025. The population of space debris generates a collision threat for operational spacecraft. However, the greatest danger is a cascading effect that could arise once the number of objects in orbit increases past a tipping point. Collisions between resident objects could generate more fragments than the atmosphere can clear, slowly rendering some orbits unusable.

The reason for the congestion in near-Earth orbital space is a collective action problem. Cooperation between space actors would increase welfare but is hampered by conflicting interests between them. Space actors generate debris because they do not take into account the underlying cost they impose on others. A space actor has very limited incentives to limit the creation of new debris as it bears all costs of its efforts, but the benefits are shared among all space actors. The financing of remediation actions to clear space from its debris faces a similar collective action problem. Management of near-Earth orbital space is complicated due to its open access and rivalrous nature. One cannot prevent a space actor from accessing an orbit, but once an actor uses an orbit, others cannot use it.

Activities in space are conducted by governments, carrying out civil and military operations, and private companies, increasing the management difficulties. The booming space economy, with plans for the launch of tens of thousands of satellites, is bound to exacerbate the space debris issue. Although the problem is global, its management is primarily undertaken unilaterally by countries. Most observers have called for coordinated actions between states, but efforts initiated locally can reduce space debris risks and drive change internationally through reciprocity.

In this work, I compare in detail different regulatory approaches aimed at mitigating and remediating space debris. While there have been numerous policy proposals, no comprehensive comparisons of the potential effectiveness, efficiency, and feasibility of policy approaches to space debris have been conducted. This work should help characterize the orbital debris issue and define the appropriate policy response. It broadens the debate on policy measures to reduce in-orbit collision risks and highlights various regulatory instruments that could achieve this goal. This work should be of interest to policy-makers, space operators and insurers, and the space community at large.

Given the limited incentives faced by space users to undertake space debris mitigation and remediation, and the substantial involvement of states in space activities, efforts solely undertaken by private actors will at best be insufficient to mitigate the problem. I thus focus my analysis on regulatory approaches and leave aside private endeavors.

In the first part of this report, I characterize the space debris problem from three interrelated angles. In chapter 2, I first describe the physical processes and the evolution of space activities that led to congestion in near-Earth orbital space. I detail the current and potential future space debris population and the risks posed by space debris. I address the different sets of actions necessary to contain the growth of debris-related risks. In chapter 3, I look at the space debris problem through an economic lens. The theory developed to characterize common-pool resources and their management can be applied to near-Earth orbital space. I look at how and to which extent the economic impacts of space debris and the benefits of mitigation can be evaluated. In chapter 4, I provide an overview of the space governance institutions and mechanisms that shape the space debris issue. The binding international treaties on outer space are anterior to the recognition of the space debris problem but form the framework in which subsequent instruments must be developed. Non-binding instruments such as guidelines have been developed to respond to the increased awareness of the unsustainable use of near-Earth orbital space.

In the second part of this report, I assess the different regulatory approaches available to mitigate space debris. I evaluate the potential effectiveness and efficiency of those measures and their feasibility, depending on the jurisdiction of implementation. In chapter 5, I discuss ongoing regulatory reforms in the United States related to space debris. They address both governmental missions and licensing requirements to operate commercial satellites. I assess ex-ante requirements for space debris mitigation through the analysis of these reforms and the stakeholders' position regarding new rules. In chapter 6, I broaden the scope of regulatory tools and look at market-based approaches. Specifically, I assess the efficiency, effectiveness, and feasibility of marketable permits, regulatory fees, insurance markets, and market-share liability and disposal payments to incentivize space debris mitigation and remediation. In chapter 7, I propose a dichotomy between the historic and yet to be created debris population to inform the choice of policy approach and discuss, for each population, the jurisdictional level at which the regulatory approaches can be applied. Finally, I conclude in chapter 8.

2 Space activities and debris creation

On October 4, 1957, the first human-made satellite—Sputnik I—was launched into orbit. Since then, about 5,560 rocket launches brought about 9,600 satellites into space (as of February 2020; ESA, 2020b). Although space is vast, most human activities in space take place in near-Earth orbital space, where satellites take advantage of their vantage point overlooking Earth for observation and communication. Two regions of orbital space are of special interest for human activities: Geostationary Earth Orbit (GEO) and Low Earth Orbit (LEO). These two regions, which are depicted in Figure 2.1, are characterized by different physical characteristics that affect the activities that can be performed. As both LEO and GEO have a significant value for human activities, they have been the most used orbital regions and are thus the most congested.

GEO is a circular orbit at an altitude of about 35,786 km with zero inclination (i.e., it is aligned with the equator). A satellite on this orbit remains above the same point on the Earth's surface as the satellite rotates at the same speed as the Earth. Thus, antennas on Earth communicating with a satellite in GEO always point in the same direction. That is particularly advantageous for satellite television and radio broadcasting.

LEO is the "spherical region that extends from the Earth's surface up to an altitude of 2,000 km" (IADC Guidelines, 2007, p. 6).[1] At these altitudes, satellites travel much faster than in GEO and take about 90 minutes to perform one revolution. Thus, satellites cannot continuously communicate with a specific receptor station on the ground. A network of satellites known as a constellation is necessary for continuous coverage of a specific location on Earth. However, as satellites are far closer to the Earth's surface, communication with them is subject to lower latency and requires lower gain antennas. The closer view of the Earth is beneficial for

[1] LEO's upper boundary can differ depending on the source defining it as LEO has no physical boundaries.

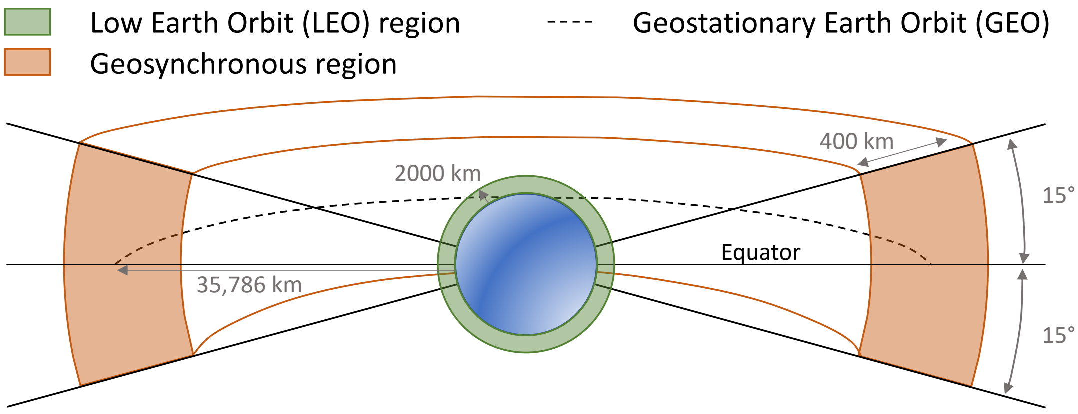

FIGURE 2.1 – Low Earth Orbit (LEO) and Geosynchronous protected regions (as defined by IADC Guidelines, 2007). The Geostationary Earth Orbit (GEO) is a particular orbit in the Geosynchronous protected region, which has zero inclination and zero eccentricity, and whose orbital period is equal to the Earth's sidereal period (illustration adapted from IADC Guidelines, 2007).

Note: Low Earth Orbit region—Spherical region that extends from the Earth's surface up to an altitude of 2,000 km; Geosynchronous region—segment of a spherical shell that extends from 200 km below the geostationary altitude (35,786 km) to 200 km above the geostationary altitude, and whose latitude is between −15° and +15° (IADC Guidelines, 2007).

remote sensing (e.g., environmental monitoring, meteorology) as it increases data resolution. Contrary to GEO, satellites have a wide variety of orbits with different inclinations and eccentricities. As it is far closer to the Earth's surface than GEO, LEO is less costly to reach as less propellant is necessary.

The region between LEO and GEO, called Medium Earth Orbit (MEO), offers a trade-off in its physical characteristics between the two most used regions. It is principally used for navigation but also communications.[2] Due to its large volume and relatively low number of satellites, MEO is less congested than LEO and GEO.

2.1 Space activities: A new era

At the start of the Space Age, activities in space were mostly conducted by governments (mainly the US and the Soviet Union). During the Cold War, the National Aeronautics and Space Administration (NASA) was created to provide

[2] MEO hosts, e.g., the GPS and Galileo systems for navigation, and the O3b constellation for communications.

"space" public goods: national security, national pride, and basic science (Weinzierl, 2018). In the mid-1960s, NASA's budget represented more than 0.7% of the US GDP. Since then, it has gradually decreased to around 0.1% of the GDP in 2016 (see Figure 1 in Weinzierl, 2018). The decrease of the share of the US budget devoted to NASA highlights the shift from a centralized control of economic activities in space to commercial ones. Two major events have shaped this transition: the Commercial Space Launch Act of 1984 and the end of the shuttle program[3] in 2011. The former created the basis for commercial launch activities while the latter created the necessary vacuum for the emergence of strong commercial launch capabilities. The burgeoning set of space companies that emerged from this decentralization is generally known as "new space" (see Table 1 in Weinzierl, 2018, for a sample of companies involved in commercial space activities).[4] Commercial launch activities have reduced the cost of launching objects in LEO by a factor of 20, enabling new activities and business models. Whereas the space shuttle cost about USD 54,500 per kg launched in LEO, SpaceX advertises a cost of USD 2,720 per kg (Jones, 2018). The space sector revenues have increased steadily from about USD 176 B in 2005 to about USD 322 B in 2015, with the vast majority of the growth in commercial activities (Space Foundation, 2018, as cited in Weinzierl, 2018; see § 3.3.1 for a broader discussion of the space industry). For a broader overview of the transformation undergoing in the space sector, see, e.g., Pelton (2017) or OECD (2019).

Since at least 2005, the Union of Concerned Scientists (2020) maintains a database of the operational satellites in orbit around Earth. Figure 2.2 summarizes the major trends in the evolution of the satellite population as monitored by this database. Over the past ten years, the number of operational satellites has more than tripled to reach 2,666 as of March 31, 2020 (see Figure 2.2(f)). The share of commercial satellites has steadily increased since 2014 to reach 58% in 2020 (Figure 2.2(a)). The number of actors present in space has also steadily increased. There are now 72 countries having at least one operational satellite (Figure 2.2(e)). Over the past 15 years, the share of satellites operated by US entities has fluctuated around 50%, while the share operated by Russian entities has decreased by four percentage points to about 6%, and the share operated by Chinese entities has increased by nine percentage points to about 13% (Figure 2.2(c)). The share of satellites in LEO has drastically increased since 2013 (Figure 2.2(d)) and can be linked to the decreasing launching costs mentioned above. Regarding applications, the share of satellites devoted to communications has decreased while the one devoted to

[3] The space shuttle program was NASA's fourth human spaceflight program. It routinely transported crew and cargo to orbit between 1981 and 2011.

[4] The miniaturization of satellite components leading to a lower cost per unit of computation in space was also a significant driver of new space ventures.

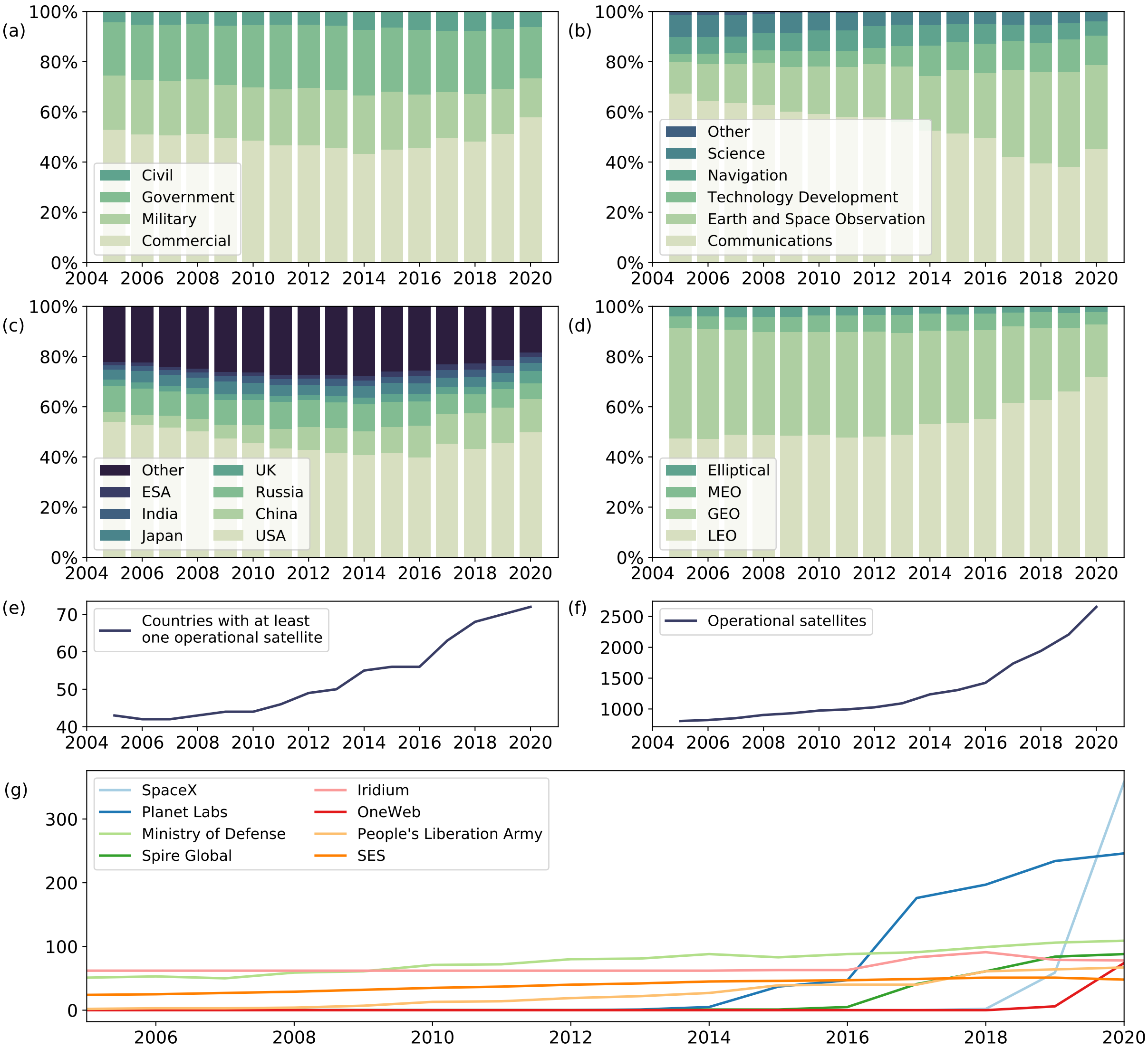

FIGURE 2.2 – Evolution of the population of operational satellites over the past 15 years (based on data from the Union of Concerned Scientists, 2020). Share of operational satellites by (a) users,[a] (b) purpose,[b] (c) country of operator/owner,[c] and (d) class of orbit.[d] Panel (e) shows the number of countries having at least one operational satellite and panel (f) shows the number of operational satellites. Panel (g) shows the number of operational satellites for the 8 operators having the largest number of operational satellites as of March 31, 2020.

Note: Data presented come from each year's last release of the database.
[a] Satellites can have multiple users. In this case, they contribute equally to each user category.
[b] Self-reported by the satellite's operator. In case a satellite has multiple purposes, it contributes equally to each purpose category.
[c] The operator is not necessarily the satellite's owner, as the satellite can be leased. If a satellite has 2 or 3 countries of operator/owner, it contributes equally to each country. Satellites with more than 3 countries of operator/owner enter the 'Other' category.
[d] LEO refers to orbits with altitude $z \in$ [80 km; 1,700 km], MEO with $z \in$ [1,700 km; 35,700 km], and GEO with $z \sim$ 35,700 km. Elliptical orbits have an eccentricity larger than 0.14.

Earth and space observation has increased (Figure 2.2(b)). However, this trend has recently reversed, notably due to the launch of the first satellites of large satellite internet constellations (SpaceX's Starlink[5] and OneWeb[6]). Established operators of satellites such as, e.g., the US ministry of defense or SES, have increased linearly the number of their operational satellites over time (Figure 2.2(f)). In contrast, new space start-ups SpaceX, OneWeb, and Planet have had an exponential growth over the past few years.

Two major trends are characteristic of new space and shaping the space environment of tomorrow (see, e.g., Jakhu & Pelton, 2017): small satellites (or "SmallSats") and large-scale constellations (or "megaconstellations"). Small satellites vary widely in terms of mass, volume, orbital characteristics, and applications. They range from CubeSats[7] used for student experiments (e.g., SwissCube[8]) or as part of start-up constellations (e.g., Astrocast[9], Spire[10]), to larger 200–300 kg satellites often as part of constellations (e.g., Starlink[11]). The upper mass limit of small satellites is generally taken as 600 kg. The trend to launch an ever-increasing number of small satellites began in the early 1990s and is expected to surge in the coming years. In 2019, 79% of the 492 spacecraft launched into orbits were small satellites (Bryce Space and Technology, 2020). The small satellites' average mass was 109 kg, and they were used for communications (37%), technology development (32%), remote sensing (26%), and other (5%). In the coming decade, the vast majority of deployments are expected to be part of commercial megaconstellations for remote sensing and communications.

The evolution of space activities since the 1970s was characterized by a rapid growth in the size and performances of commercial satellites. The focus has been on large GEO satellites used for TV and radio broadcasting, as well as telecommunications. As of today, TV and radio broadcasting satellites in GEO still account for the vast majority of satellite services revenues (Satellite Industry Association, 2019). Due to the transmission distance, there is high latency (or transmission delay) when communicating with a satellite in GEO, which is not optimal for broadband internet. In LEO, the latency is significantly diminished, and less powerful amplifiers are necessary for successful transmission, but a large number of satellites is necessary to provide global coverage.[12] Moreover, as satellites are moving on the sky, they

[5] See https://www.starlink.com.

[6] See https://www.oneweb.world.

[7] A CubeSat is a small satellite made of multiples standardized 10 cm^3 cubic units. They often use commercial off-the-shelf components for their electronics and structure.

[8] See https://archiveweb.epfl.ch/swisscube.epfl.ch/.

[9] See https://www.astrocast.com.

[10] See https://spire.com.

[11] See footnote 5.

[12] The number of satellites needed for global coverage depends on the altitude and the constel-

need to be tracked by the receiver. In the 1990s, small satellite constellations (50 to 70 satellites) have been deployed in LEO by Iridium, Globalstar, and Orbcomm to provide global telecommunications (voice, messaging, or data). These three companies went bankrupt, mainly due to a lack of demand for the services proposed at the prices offered. After a financial restructuring, they became financially viable as they could offer lower prices resulting in a higher demand for their services (see Bloom, 2016, on the Iridium story). The increase in demand for internet-based services coupled with the decrease in launch and manufacturing costs, the miniaturization of satellite components, and new architectures have revived the interest for LEO satellite internet constellations. At the same time, increased connectivity and computation capabilities enable new business models. The development of constellations for remote sensing is one such example.

In the past five years, numerous commercial companies have proposed, funded, and in a few cases even begun the deployment of megaconstellations of small satellites. Figure 2.3 depicts the largest planned constellations. The upper panel shows the number of planned satellites alongside the number of operational satellites in 50 km altitude bins. Whereas there are currently about 2,600 operational satellites orbiting Earth, companies have plans for placing over 20,000 satellites in orbit in the coming decade.[13] However, there is high uncertainty as to when and if those constellations will be completed. Moreover, these endeavors require a tremendous amount of capital which is difficult to secure, as there is a lack of certainty regarding the demand for satellite-based internet (see Appendix C, which illustrates the difficulty in estimating the demand).[14] The availability of low-cost technology for user terminals will be a necessary component to enable those constellations to be successful.

2.2 Space debris

Space debris, also referred to as orbital debris or space junk, is defined as "all artificial objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional" by the Inter-Agency Space Debris

lation design. The higher the altitude, the lower the number of satellites required.

[13]This does not include OneWeb's recent request to the FCC to increase the number of satellites in its constellation up to 48,000 (OneWeb, 2020b). SpaceX's last filing to the FCC for 30,000 more satellites is also not included (Patel, 2019).

[14]The uncertainty lies more in the combination of price and service offered by satellite constellations rather than internet demand. Users are likely indifferent to the medium used to have internet. The size of the demand will thus be principally affected by the service price.

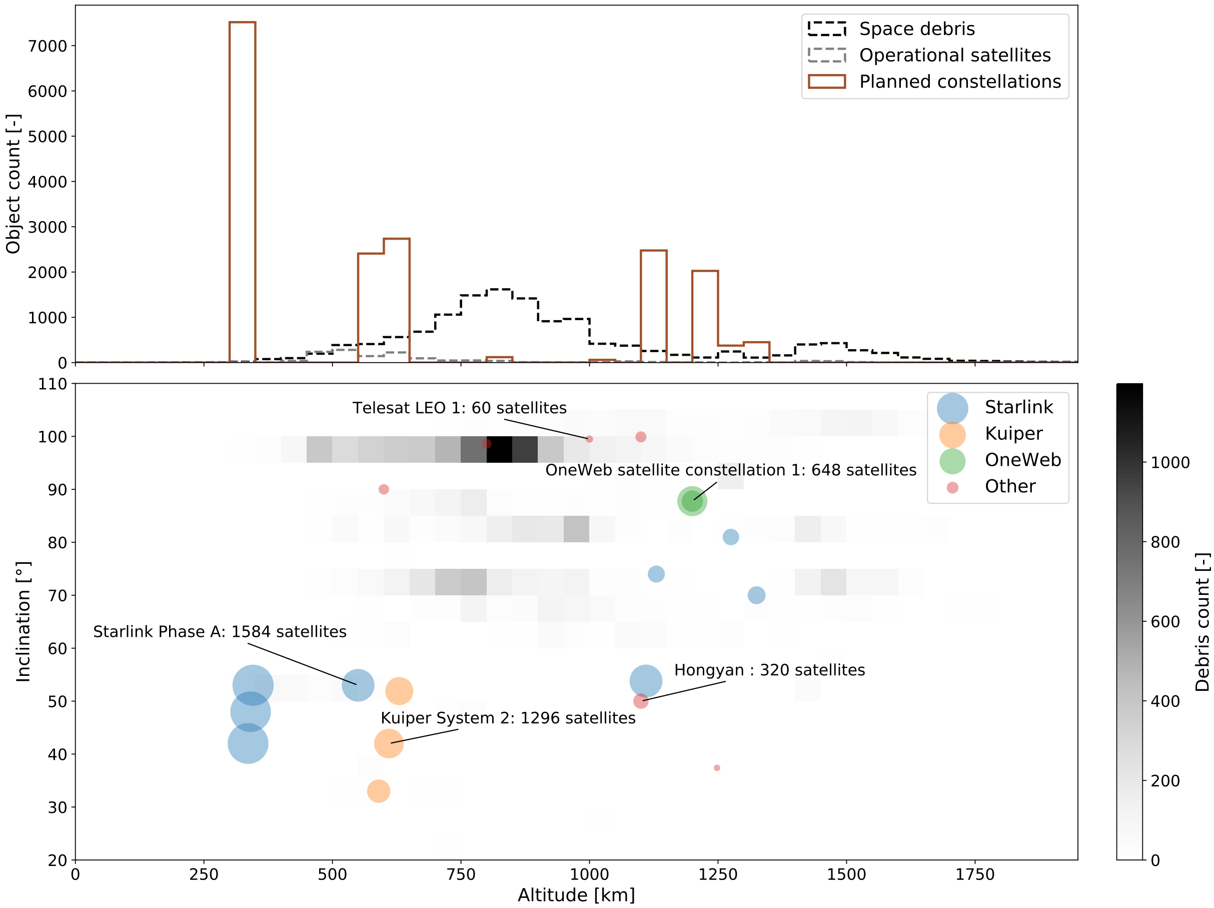

FIGURE 2.3 – *Top panel:* Number of debris, operational satellites, and satellites in planned large constellations per 50 km altitude[a] bin. *Bottom panel:* Number of trackable debris per altitude and inclination bin (50 km × 5°), and planned satellite constellations. The area of the bubbles representing the constellations is proportional to their number of satellites.

Note: Bins in the bottom panel do not truly represent the density of objects as the bins have an increasing volume with increasing altitude. Space debris data is from 18 SPCS (2020, as of January 7, 2020), and operational satellites from the Union of Concerned Scientists (2020, as of September 30, 2019). Planned constellation data is from publicly available information, including FCC fillings, newspaper articles, and companies' websites. Constellations depicted in this figure are listed in Table A.1.

[a] The altitude is the average between the perigee and apogee.

Coordination Committee (IADC Guidelines, 2007). Space debris is a byproduct of space activities and encompasses a wealth of objects with diverse sizes, generating processes, and harm potentials. In § 2.2.1, I first discuss how debris is generated and removed from orbit. I then detail the current debris population and the main events that generated it in § 2.2.2. At the same time, I present how the debris population is tracked and modeled. In § 2.2.3, I detail the risk operational assets face from space debris. Finally, I discuss the potential evolution of the space debris population in § 2.2.4.

2.2.1 Source and sinks

The evolution of the space debris population is a balance of sources and sinks (Bonnal & McKnight, 2017). Four sources of space debris are commonly defined (H. A. Baker, 1989):

1. *Inactive payloads:*[15] "[F]ormer active payloads which can no longer be controlled by their operators" (p. 4). This category includes satellites that have reached their end-of-life (EOL) and cannot be de-orbited because they do not have any propellant left or do not have propulsion capabilities and satellites for which the operator has lost control.
2. *Mission-related objects:* "Objects associated with space activities, which remain in outer space" (p. 4). The major contributor to this category is rocket bodies, which have been left in orbit after serving their purpose. Other hardware released during operations includes, e.g., lens covers, bolts, fairings, multi-layer insulation, and payload separation hardware.
3. *Fragmentation debris:* Debris generated when space objects break-up through explosions and collisions.
4. *Micro particulate matter:* Debris ranging between 1 and 100 microns, including, e.g., solid rocket motor firings, ejecta material released through small-particles impacts, and degradation products (e.g., paint flakes).

Only two sinks are available to clear space debris from orbits: atmospheric drag and direct retrieval. Although space is often defined as starting from 100 km above our head, there is no outer edge to the atmosphere. Atmospheric density decreases

[15] "Payloads are space object designed to perform a specific function in space excluding launch functionality." (ESA Space Debris Office, 2019, p. 5)

with altitude but does not vanish completely in near-Earth space. Over many revolutions, the cumulative effect of the atmosphere on satellites is not negligible and slowly drags them down. The density of the atmosphere is affected by the solar cycles, which last 11 years. The strength of these cycles and thus the resulting atmospheric drag is difficult to predict. The lifetime of a piece of debris depends on the ratio between its cross-sectional area and its mass, its altitude, and solar activity. This is illustrated in Figure 2.4, where the predicted orbital lifetimes for three different objects in circular orbits are shown. In GEO, due to the quasi absence of atmosphere, objects are not dragged down and can last millions of years (H. A. Baker, 1989). Uncrewed direct retrieval from orbit has not yet been performed and is addressed in § 2.3.

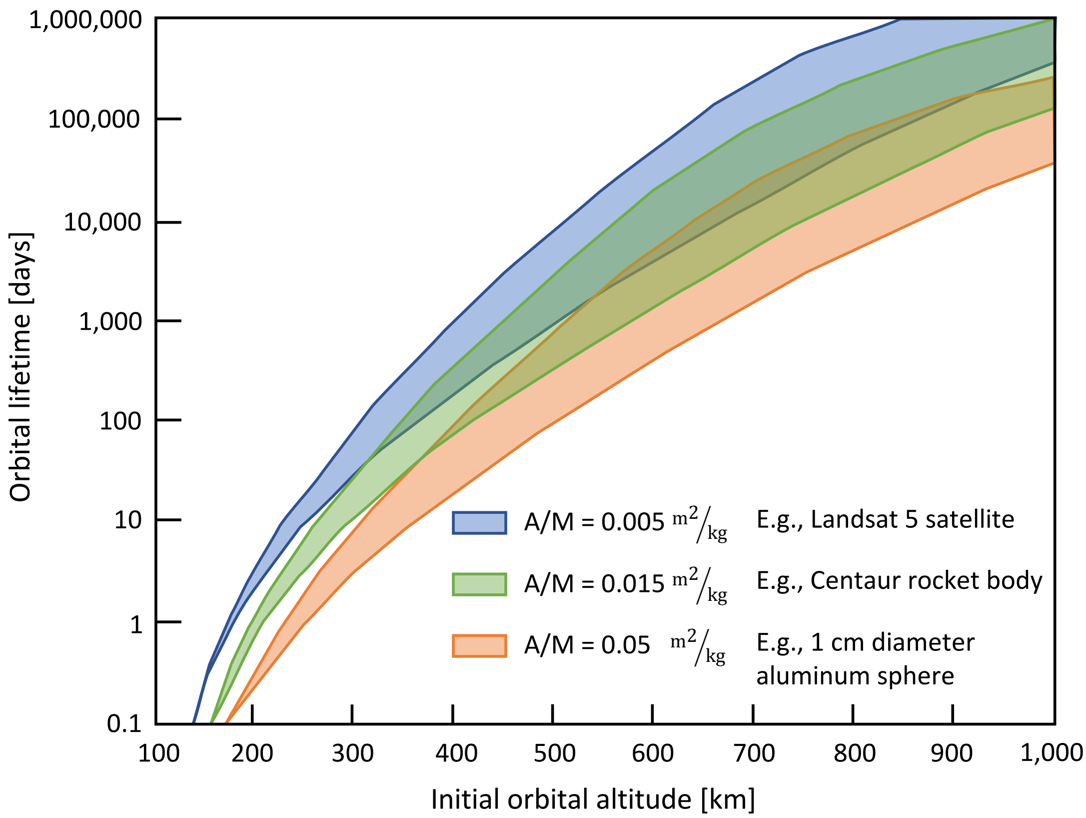

Figure 2.4 – Orbital decay time versus altitude for circular orbits (adapted from National Research Council, 1995, Figure 1-6, p. 29).

Note: The upper line is at solar minimum ($F_{10.7} = 75$) and the lower line is at solar maximum ($F_{10.7} = 175$).

As the number of space debris increases, the probability of a collision between them also increases. When a collision happens, it generates fragments that further increase the probability of a collision. This secondary debris can then collide and generate even more debris. This cascading effect where space debris becomes self-generating is known as the *Kessler Syndrome* and has been first hypothesized in 1978 (Kessler and Cour-Palais). Past a tipping point, even without any new launches, the number of objects orbiting Earth could increase exponentially with time. The time scale on which such a cascading effect occurs can be large, and the tipping point is difficult to identify.

2.2.2 Current debris population

Due to difficulty in monitoring space debris, there is uncertainty regarding the current number of debris in orbit. Figure 2.5 summarizes the sources of debris and the measurement means by debris diameter. Current technology can reliably detect and catalog objects approximately larger than 10 cm in LEO and larger than 80 cm in GEO (Bonnal & McKnight, 2017).[16] The population of smaller objects is modeled based on the impacts observed on exposed surfaces from spaceflight that have been returned to Earth and on collisions and explosions data. The most advanced modeling programs that detail the flux of debris particles in Earth orbit are the Orbital Debris Engineering Model (ORDEM) developed by NASA and the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) developed by the European Space Agency (ESA; see Krisko et al., 2015, for a comparison between MASTER and ORDEM).

ESA's statistical model of the debris population estimates that there are 128 million objects in the 1 mm to 1 cm size range, 900,000 objects in the 1 cm to 10 cm size range, and 34,000 objects larger than 10 cm (ESA, 2020b, as of February 2020). The US Space Surveillance Network (SSN) tracks and maintains a catalog of about 22,300 objects according to ESA (2020b, as of February 2020), but the publicly available catalog contains only 20,659 objects (18 SPCS, 2020, as of May 22, 2020), out of which 15,193 (73.5%) are in LEO.[17] The distribution of those cataloged objects across altitudes by object type and size is presented in the upper panel, and lower panel, respectively, of Figure 2.6.

As depicted in Figure 2.7, the current population of space debris accumulated

[16]The deployment of the Space Fence, a radar system, could increase by an order of magnitude the number of debris tracked by the US Space Surveillance Network, as debris as small as 5 cm could be tracked (Gruss, 2019). In March 2020, the US Space Force has announced that the Space Fence is operational, but the impact on the number of cataloged objects has not yet been observed (Erwin, 2020a).

[17]Satellites whose altitude (the average between perigee and apogee) is lower than 2,000 km are considered in LEO.

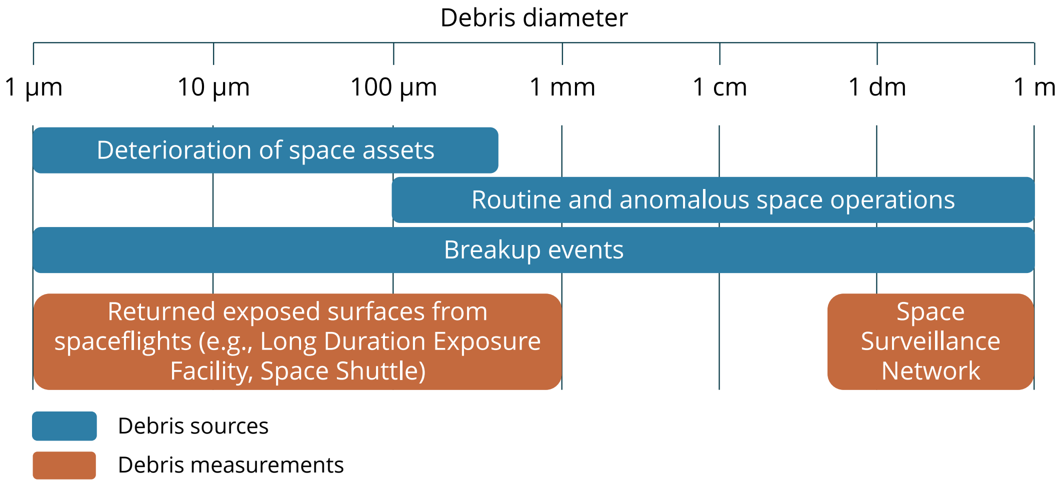

FIGURE 2.5 – Sources of debris and means of observation by debris diameter (adapted from Bonnal & McKnight, 2017, Figure 1).

gradually over time as a byproduct of space activities. Since the beginning of the Space Age, there have been more than 500 break-ups, explosions, collisions, or anomalous events resulting in fragmentation (ESA, 2020b). Fragmentation events represent the most abundant source (58%, as of March 2017) of the trackable debris population. On-orbit fragmentation events are inferred from the detection of new objects and their orbits' correlation with a common source. The dominant cause of break-ups are deliberate destruction, propulsion-related explosions, battery explosions, and four known accidental collisions Bonnal and McKnight (2017).[18] The deliberate destruction of the Chinese satellite Fengyun-1C orbiting at an altitude of 865 km in January 2007 accounts for the largest absolute growth of the debris catalog. The Chinese anti-satellite (ASAT) missile test resulted in 3,433 trackable fragments (a 34% increase in the trackable debris population). The second-largest generative event is the accidental collision between the active commercial satellite Iridium 33 and a derelict Russian military satellite Cosmos-2251, which generated 2,296 trackable fragments (a 22% increase in the trackable debris population).

[18] See Table 2.2 in Bonnal and McKnight (2017) for the ten on-orbit break-up events with the highest counts of cataloged fragments. Note that the cause of many events is unknown.

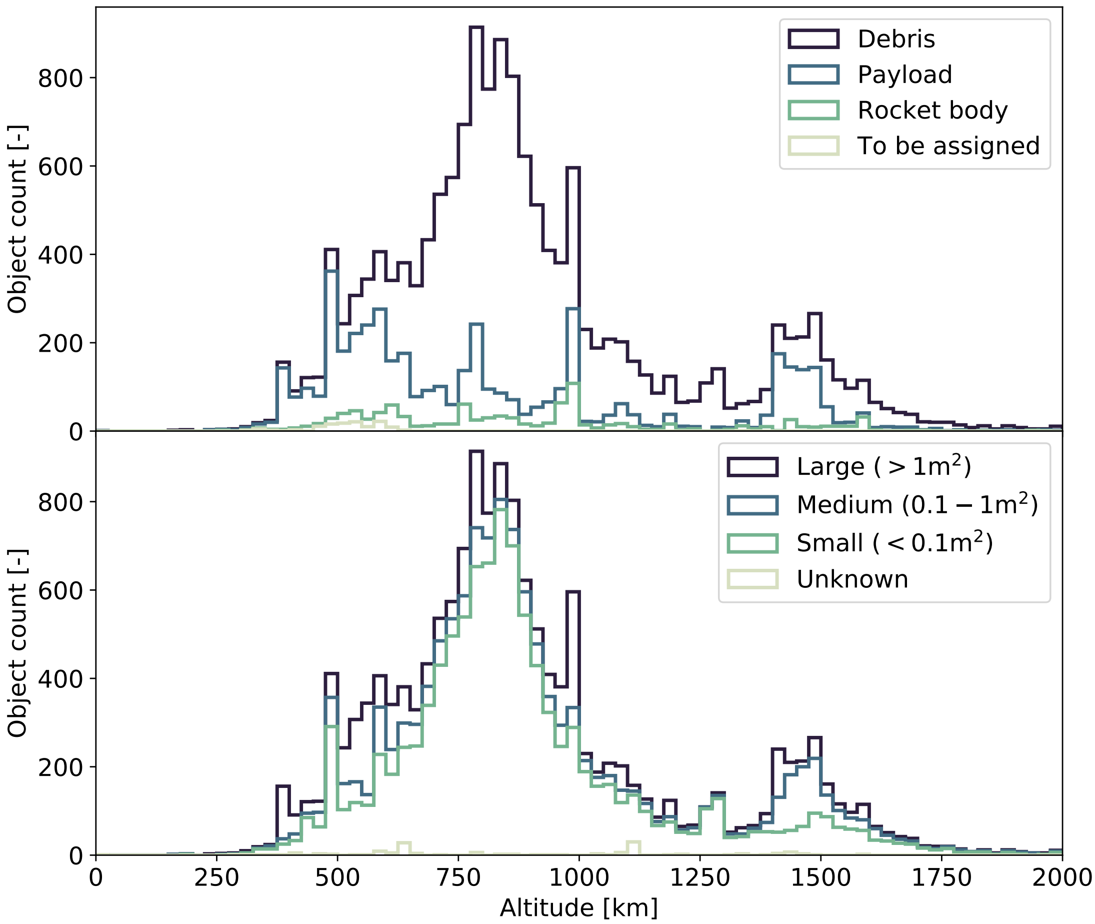

FIGURE 2.6 – Publicly available catalog of space objects (SATCAT) tracked by the US SSN (18 SPCS, 2020, as of May 22, 2020). *Upper panel:* Altitude of objects by type. *Lower panel:* Altitude of objects by size (radar cross section).

Note: The 'Payload' category comprises both operational and non-operational objects.

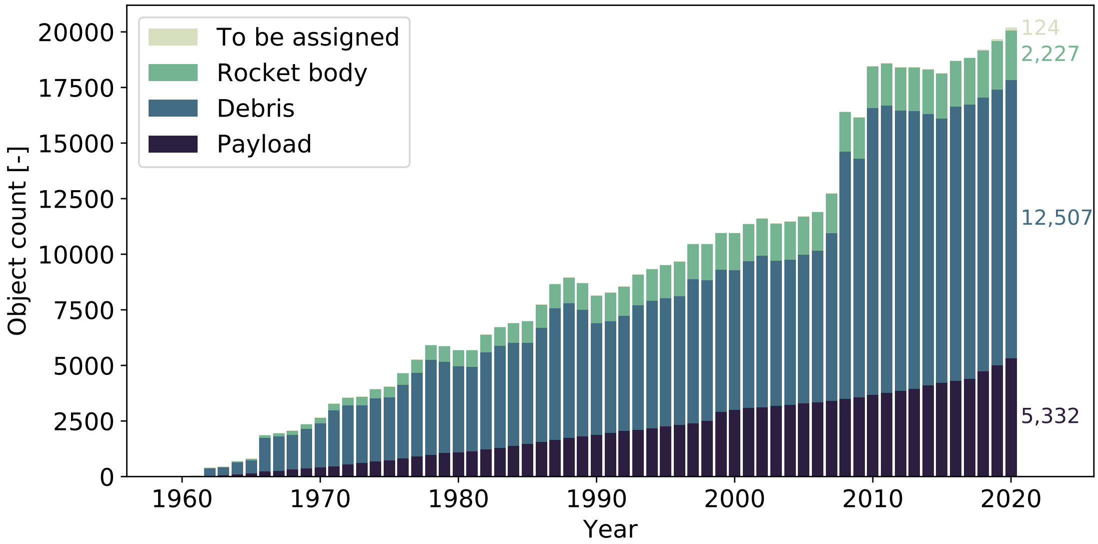

FIGURE 2.7 – Evolution of the number of objects in orbit by type.

Note: Numbers displayed on the right are as of January 1, 2020. Data on launch and reentry epochs is from the publicly available catalog of space objects (SATCAT) tracked by the US SSN (18 SPCS, 2020). Data on fragmentation events is from the DISCOS database (ESA, 2020a). For the evolution of mass and area in orbit by type, see ESA Space Debris Office (2019, Figure 2.1).

2.2.3 Risks posed by space debris

The presence of debris in orbital space creates a collision risk for operational spacecraft. Of all orbital regions, LEO has the highest collision probability—at least three orders of magnitude greater than in any other regions, including GEO (Bonnal & McKnight, 2017). This is due to the highest density of debris and higher orbital speeds in LEO. Satellites have an orbital speed of about 3 km/s in GEO and 7–8 km/s in LEO. Collisions in LEO can thus have significantly greater impact velocities.

Two types of collisions must be distinguished: 'catastrophic' collisions which result in the complete fragmentation of a piece of debris or operational spacecraft and 'lethal' collisions which disable[19] an operational spacecraft. A commonly used measure of a collision intensity is the energy-to-mass ratio (EMR)

$$\mathrm{EMR} = \frac{E_{\mathrm{imp}}}{M_{\mathrm{tar}}} = \frac{M_{\mathrm{imp}} \cdot v_{\mathrm{rel}}^2}{2 \cdot M_{\mathrm{tar}}}, \tag{2.1}$$

where M_{imp} and M_{tar} are the mass of the impactor, and the target, respectively,

[19] Collisions can also affect the performances of a spacecraft or disable some subsystems.

v_{rel} is the impact velocity between the objects, and the impactor is the smallest object. The collision is assumed to be catastrophic if the EMR exceeds 40,000 J/kg (McKnight et al., 1995). For example, assuming the density of space debris objects is similar to that of aluminum and that collisions with relative velocities of up to 14.5 km/s can occur, the threshold for catastrophic collisions for a 150 kg satellite (e.g., a OneWeb satellite) is reached for impactor debris with diameters of about 3 cm (Radtke et al., 2017). Debris with EMR below the threshold can still damage an operational spacecraft, but spacecraft shielding can protect from high impact velocity debris for objects smaller than about 3 mm (Gwenaëlle et al., 2012). Collision with larger debris will result in the loss of spacecraft capabilities, and in the worst case, the loss of the entire spacecraft. As disentangling technical failures from impacts with small debris is difficult, the cause of a loss of a spacecraft is often unknown (see Swiss Re, 2018, Table 2, for a list of potential lethal collisions with small debris).

For operational spacecraft, the collision risk can be divided into two broad categories depending on the debris trackability: large debris (approximately bigger than 10 cm with current technology) can be tracked and thus dodged if the spacecraft is maneuverable, and small debris (approximately smaller than 10 cm), which cannot be avoided. However, uncertainties in the positions of cataloged objects can significantly impede debris dodging.[20] A collision with large debris would always result in a catastrophic collision, while a collision with small debris could result in a catastrophic collision or the loss of the spacecraft depending on the EMR of the collision. McKnight (2010, p. 4) notes that the primary concern is posed by cm-size space debris as they are "large enough to terminate a mission upon impact, cannot be seen reliably from the ground, and yet are 10–100 times more populous than the cataloged population."

2.2.4 Future debris population

Predicting the future debris population is even more arduous than estimating the current one. The postulation of a cascading effect whereby the generation of space debris via collisions could lead to an exponential increase in orbital debris rendering some orbits unusable (Kessler & Cour-Palais, 1978) led to efforts in modeling the

[20] The positions of debris and spacecraft are not known precisely but have large uncertainties (see, e.g., Levit & Marshall, 2011). Thus, decisions to maneuver are taken based on probabilities. This probabilistic measurement implies that encounters with low probability can still lead to a collision, and close encounters are sometimes identified too late to make a maneuver. For large debris, the current typical accuracy is in the order of ± 1 km along the velocity vector and ± 200 m in the radial direction (Peterson et al., 2018, as cited in Bonnal et al., 2020).

space environment and its evolution.

Assuming that no object was launched in space after December 2004 and that no future disposal maneuvers were allowed for existing spacecraft, Liou and Johnson (2006) showed that beyond 2055 the population of space debris increases as the creation of new collision fragments exceeds the number of decaying debris. The debris population increase predicted by their model is nonuniform across altitudes and is the strongest where the current debris population is the largest (i.e., 800–1000 km). They stated that "[t]he current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future" (Liou & Johnson, 2006, p. 340). Further studies have confirmed that the tipping point of the Kessler Syndrome might already have been reached (e.g., Liou & Johnson, 2008).

Subsequent studies have analyzed the impact of the future launch traffic and various policy measures on the space debris population. The use of active debris removal (ADR) to stabilize the debris population has been particularly studied (e.g., Liou & Johnson, 2009; Liou et al., 2010; Virgili & Krag, 2009). Liou et al. (2010) showed that the debris population in LEO could be stabilized in the next 200 years with an ADR rate of five objects per year. However, this landmark study was made before the advent of new space and assumed a future launch traffic similar to the historical one. Recently, the impact of large satellite constellations on the space debris population has been studied (e.g., Liou et al., 2018; Lucken & Giolito, 2019; Olivieri & Francesconi, 2020; Radtke et al., 2017; Somma et al., 2019).

Overall, the majority of the studies conducted on the future of the space environment concluded that compliance with the current international mitigation standards (see § 4.2.3) and the retrieval of at least five large objects per year were a *prerequisite* for keeping space activities sustainable on the long term.[21] These findings have triggered studies on the debris-generating potential of the current debris population aimed at establishing priority lists for ADR missions (e.g., Kebschull et al., 2014; Letizia et al., 2018; Rossi et al., 2015). However, modeling of the future space environment is highly sensitive to the assumptions regarding certain input parameters. By broadening the values of four of them, describing launch and explosion rates, the magnitude of solar activity, and the level of post-mission disposal compliance, White and Lewis (2014) showed a high variance in the future LEO debris populations. Under some assumptions, no ADR was required to stabilize the debris population, while with others, more than ten removals per year were required.

[21] Earlier studies looked at the number of retrievals required to stabilize the debris population. Those were performed without assuming a large increase in the launch traffic. More recent studies that take into account up-to-date launch traffic predictions are more focused on the effect of the level of successful post-mission disposal and lowering the 25-years rule.

As active constellation satellites can potentially dodge cataloged space debris, clusters of derelict uncontrolled objects might represent a bigger long-term risk to the space environment (McKnight et al., 2019; Rossi et al., 2019). Members of debris clusters are large spacecraft and upper stages whose collisions would result in a large number of fragments. McKnight et al. (2019) have identified six LEO clusters with a high debris-generating risk, some of which are located at high orbital altitudes and thus would result in long-lived fragments.

2.3 Debris related actions

Reducing the space debris growth and the negative impact debris has on space operations relies on three building blocks (McKnight & Maclay, 2019): Space Situational Awareness (SSA), Space Traffic Management (STM), and Space Environment Management (SEM). Their relationships are summarized in Figure 2.8.

SSA is the foundation of all debris related action. It "includes perceiving orbital anomalies or threats, maintaining an inventory of objects as completely as possible, and developing and providing timely information for collision avoidance and safe operation" (Bonnal & McKnight, 2017, p. 43). Without the required data on the space environment, STM and SEM cannot be conducted. STM is "the planning, coordination, and on-orbit synchronization of activities" (SPD-3, 2018) and is aimed at preserving operational space assets. STM activities, such as conducting collision avoidance maneuvers, can only be performed by maneuverable spacecraft. However, only about 7.5% of the trackable population of space objects is maneuverable (Bonnal et al., 2020). Thus, the majority of in-orbit collisions cannot be avoided through enhanced STM capabilities. To avoid collisions among the non-controllable space object population, SEM actions are required. The first step consists in mitigating the risk of debris-generating collisions by reducing the sources of space debris (e.g., reducing the number of debris released through normal operations, or the number of satellites lost through better shielding or more reliable components). Bonnal and McKnight (2017, p. 115) observe that "because of the time and cost necessary to modify designs and operations practices, the debris problem has a significant time lag between the recognition of the issues and the effect of changes." If mitigation actions are taken too late or are insufficient, remediation becomes necessary (see Figure 2.9 for a summary of mitigation and remediation actions). The predictions of the future space debris population presented in § 2.2.4 highlighted the need for compliance with strict mitigation standards and remediation activities. Bonnal et al. (2020, p. 638) note that a collision in a cluster of derelict objects in LEO "would generate a very large number of new debris and trigger a situation which may turn out to be non-sustainable at medium to long term" (Bonnal et al., 2020, p. 638). Avoiding this unsustainable situation requires remediation activities, which can take two broad forms (Kessler et al., 2010): removing debris from orbit and slightly changing debris trajectories before their predicted collisions. The "strategic" approach consists of actively removing a certain number of derelict objects to reduce the probability of major collisions. In contrast, the "tactical" approach consists in lowering the probability of a predicted collision by affecting the trajectory of one of the two pieces of debris prior to the predicted collision time (Bonnal et al., 2020). This approach, called Just-in-time Collision Avoidance (JCA), requires accurate debris positions, which are not currently available (see § 2.2.2). Different JCA methods have have been proposed such as using an orbital laser, through a system releasing a cloud of particle and gas in front of a piece of debris, or using a swarm of nano-tugs attached to a piece of debris to modify its trajectory (Bonnal et al., 2020).

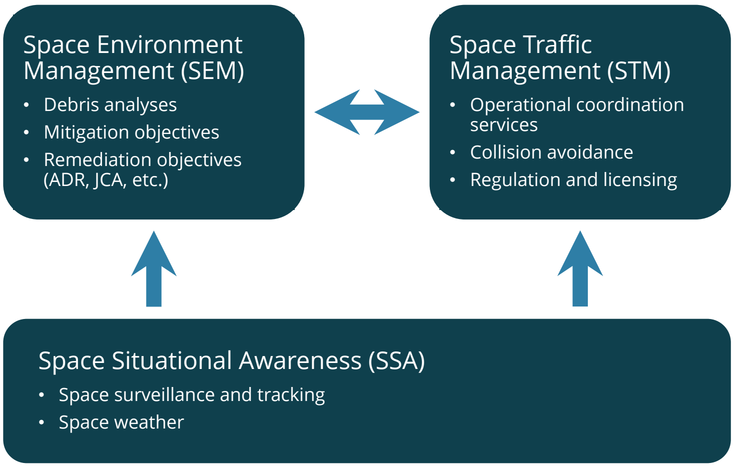

Figure 2.8 – Relationships between space debris related actions (adapted from Bonnal et al., 2020, Figure 1).

In 1984, the space shuttle brought back to Earth two satellites, which had been placed into incorrect orbits. The capture was performed by astronauts during a spacewalk (see National Space Society, 2011, for a video of the capture).[22] This type of crewed mission is extremely costly and would not make commercial sense. Numerous methods that do not require humans to perform ADR missions have been envisioned (see Shan et al., 2016, or Mark & Kamath, 2019, for a review), but no in-orbit demonstration has been performed so-far. Two companies—Astroscale

[22] Note that the satellites could be controlled: their altitude and rotation was lowered from the ground.

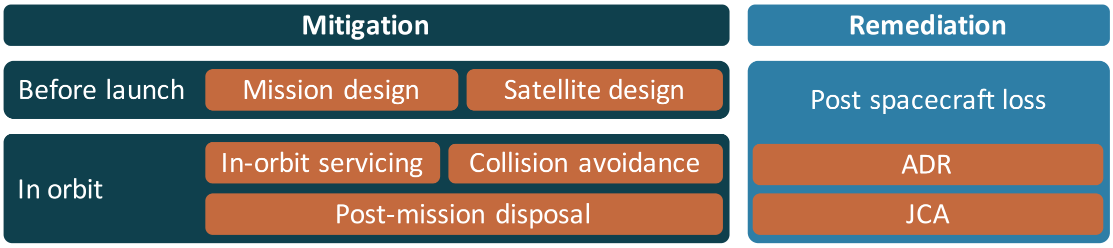

FIGURE 2.9 – Summary of mitigation and remediation actions in the space debris context (adapted from Oltrogge, 2020, slide 10).

and ClearSpace—are currently working towards the first uncrewed ADR missions. In 2020, Astroscale will launch its End-of-Life Service by Astroscale demonstration (ELSA-d) mission, whose aim is to test the technologies necessary for debris docking and removal (Forshaw et al., 2019). A chaser and a target will be launched together. The chaser will release the target and capture it under different configurations to demonstrate key ADR capabilities. Astroscale has also been selected for the first phase of the Commercial Removal of Debris Demonstration (CRD2) project, an ADR mission funded by the Japan Aerospace Exploration Agency (JAXA), which consists in sending a spacecraft to inspect a discarded Japanese rocket upper stage (Henry, 2020a). This first phase, which shall be completed before March 31, 2023, is the first step towards removing the rocket upper stage. The first removal of a derelict object should be conducted by the ClearSpace-1 mission, which is scheduled for launch in 2025. This mission is led by the Swiss start-up ClearSpace and has received about EUR 120 M funding from the ESA in November 2019. The target of the mission is a Vega Secondary Payload Adapter (VESPA) weighing 120 kg with an 800 km by 660 km altitude orbit (ESA, 2019).

The rendezvous and capture of a non-cooperative, unprepared, tumbling object is a challenging task that requires various technologies (e.g., Bonnal et al., 2013) but appears to be feasible in the near-term. However, performing ADR missions is not only technically challenging but also raises legal, political, and economic issues (Emanuelli et al., 2014). The latter are addressed in the remainder of this work as part of a broader analysis of policies for space debris mitigation and remediation. Indeed, as Bonnal et al. (2020, p. 638) notes "[ADR] would be quite useless as long as the mitigation rules, internationally agreed-upon, are not complied to in a much higher way; there is no use in going to de-orbit a couple of large debris as long as we generate more of them continuously." There needs to be a comprehensive approach to both mitigation and remediation.

3 Economics of space debris

Space debris is a byproduct of space exploration and exploitation. As useful orbital space is not infinite, debris creates a congestion problem. The debris population imposes a cost on current and future space users. When generating debris, space actors impose a cost on other users of orbital space, without their consent. In this sense, space debris is a classic example of a negative externality. In this chapter, I first characterize the space debris problem in economic terms (§ 3.1). I then discuss the incentives space users have in mitigating space debris (§ 3.2). Then, I take a broad look at the space industry and address the challenges in estimating the value of near-Earth orbital space and the cost of space debris (§ 3.3). Finally, I detail the few theoretical economic models that have been developed to explain the economic consequences of space debris (§ 3.4).

3.1 The tragedy of the space commons and its solutions

Orbital space in LEO is scarce but can be freely accessed. It is rivalrous as one's use of a particular orbit prevents other space actors from using it. Moreover, its use is non-excludable; i.e., it is costly to exclude actors from enjoying the benefits of orbital space. These two characteristics—subtractability of use and excludability—renders orbital space in LEO a common-pool resource (CPR). This type of good faces a management problem known as the "tragedy of the commons" (Hardin, 1968). Individuals' failure to integrate the costs they impose on others when consuming the resource leads to an overconsumption of the resource, potentially leading to its depletion. At the same time, efforts from one individual to maintain the resource accrue to all actors and are thus underprovided. Two traditional remedies are often proposed to the tragedy of the commons: government control or private property rights. The former usually takes the form of a Pigouvian tax (Pigou, 1932), which raises the private cost such that actors generating space debris consider both their private cost and the social cost in taking their decisions. However, this solution faces two obstacles: the knowledge and incentive problems. The public sector might not have sufficient knowledge to implement an optimally sized tax, and even if it has the knowledge, solving the problem might not be in its interest. I explore Pigouvian taxes in more depth and their application to space debris in § 6.2. The second solution commonly applied to the tragedy of the commons is private property rights. Coase (1960) pointed out that externalities emerge from imperfect or absent property rights. When property rights are clearly defined, it is possible to determine which party must bear the cost of conducting a particular activity. Provided that negotiations and enforcement costs are negligible, the resulting pollution level will maximize efficiency. In other words, the tragedy of the orbital commons stems from its open-access nature. By assigning property rights, space actors would have an incentive to maintain and keep their property uncluttered. However, how could property rights be allocated in space? The international legal regime characterizes space as "the province of all mankind" (Outer Space Treaty, 1966, Article I) and prevents "national appropriation by claim of sovereignty, by means of use or occupation, or by any other means" (Outer Space Treaty, 1966, Article II), rendering attempts at establishing property rights in space difficult.[1] Aside from the legal obstacles, defining property rights in space faces physical obstacles. Satellites use different combinations of eccentricities and inclinations, making the allocation of a certain volume of space difficult. Defining the appropriate volume to allocate would also be a challenge (A. W. Salter, 2016). Reaching an international agreement regarding the scope and the allocation of property rights seems intractable. As Demsetz (1967, p. 350) notes: "property rights develop to internalize externalities when the gains of internalization become larger than the cost of internalization." In other words, if the cost of defining and enforcing property rights is higher than the gains generated by those property rights, it is more efficient not to create them. Government control and private property rights are extrema in the spectrum of institutions available to manage CPRs. Work by E. Ostrom (2015) and colleagues have unveiled many empirical examples of successfully managed CPRs that do not rely on those two options. By observing the self-governing institutions created by communities around the globe to manage their CPRs, E. Ostrom (2015) has devised a set of conditions that are

[1]Note that in practice, as constellations can hardly coexist at the same altitude, there is some form of appropriation of space by constellation operators. For example, once Starlink is completed, it is unlikely that another operator will be able to launch a constellation at the same altitude without taking an unbearable level of risk. It is unclear how the Outer Space Treaty (1966) provision on non-appropriation by means of use or occupation should apply to constellations in near-Earth orbital space. See C. D. Johnson (2020) for a discussion on this topic.

instrumental in the sustainable management of CPRs. However, fostering these conditions in the management of a global CPR such as orbital space in LEO is challenging.

In Appendix B, I discuss in further depth the definition and characteristics of CPRs (§ B.1), the management problem they face (§ B.2), the methods devised to ensure their sustainable management (§ B.3), and the application of this perspective to near-Earth orbital space (§ B.4).

3.2 Mitigation incentives and collective action

Due to the absence of property rights for orbital paths and a weak in-orbit liability regime (see § 4.1.1.2), satellite operators cannot recover collision-related costs imposed on them by others (see, e.g., Rao et al., 2020). An operator has a limited incentive to reduce the amount of debris it generates, as it solely bears the costs of reduction, but the benefits are shared among all space users. Operators have an interest in preserving their operating assets from collisions and explosions; thus, they will invest, e.g., in shielding, maneuver capabilities, or conjunction data analysis. However, once a satellite has reached its end-of-life (EOL), operators no longer have any incentive to preserve their satellites from collisions and explosions, e.g., by de-orbiting them. The post-mission disposal (PMD) of spacecraft at their EOL does not provide direct benefits for operators but is costly (e.g., more propellant needed, shorter lifetime). Similarly, operators have no incentive in reducing the debris generated through normal operations, as these do not affect their bottom line.

3.2.1 A comparison with greenhouse gas emissions

The space debris problem is global in nature and bears many similarities with greenhouse gas (GHG) emissions. Local solutions are important steps, but coordination and rule harmonization are necessary to cope with the problem, as actors can shift the polluting activity from one jurisdiction to another (see § 7.2.2 for a discussion of the impact of unilateral action in the space debris context). In both problems, mitigation and remediation activities are necessary, but action is difficult to mobilize as the negative effect of the pollution will only materialize in the distant future (see, e.g., D. Johnson & Levin, 2009). Also, the earlier steps are taken, the lower the overall cost of dealing with the problem will be. Compared to GHG, space debris seems a more tractable problem for the following reasons:

- Actors responsible for space debris creation are also the ones affected by them. Although pieces of debris generated today will only affect their operation in the distant future, operators still have some incentive to reduce them. In the case of GHG, most emitters are not directly affected by global warming.
- The number of spacefaring nations is smaller than the number of states emitting GHG. International agreements negotiated among states are consensus-based, thus the smaller the set of participants, the easier a solution can be reached. However, the major spacefaring nations are the US, Russia, and China, which have diverging interests and have shown a lack of interest in multilateral diplomacy.
- The remediation solutions available for space debris appear far more manageable than for GHG, at least if undertaken before a significant number of catastrophic collisions generate a larger population of small fragments. Technologies to retrieve large derelict objects from orbit will soon be ready for use. In contrast, once GHG is emitted, it is technically difficult to remove it from the atmosphere (see, e.g., Ranjan & Herzog, 2011, on the feasibility of CO_2 air capture).
- Trackable and identifiable space debris can be linked to a space actor, while GHG in the atmosphere cannot be linked to an emitter. The ability to monitor part of the pollution ex-post increases transparency and helps rules enforcement.
- Actors responsible for space debris generation are only states and private companies. In the case of GHG, decisions by individuals also affect the level of emissions. Awareness of the problem and its consequences is likely more difficult to communicate to the general population than to a limited set of companies and governments.

However, addressing the space debris problem encompasses military considerations that are not present in GHG emissions. Outer space is a strategic domain, and rules for space activities affect military operations. Entanglement between space debris and peaceful use of outer space has slowed international negotiations on the issue. Furthermore, ADR technologies have dual-use capabilities. As they can be used both to de-orbit a piece of debris or damage a functional satellite, it increases the complexity of the rules to be enacted and their negotiation (e.g., Frigoli, 2019).

Although ADR systems can be used for harmful purposes, "the technology of the ADR system is probably not practical for the conduct of massive ASAT attacks if developed in a scope proposed by the supporters of active debris mitigation" (Dobos & Prazak, 2019, p. 222). The intent of ADR systems users determines its primary function, thus "if the ADR systems are to be effectively utilized in the civil sector, the actor operating them must be perceived as reliable by the vast majority of the international space community" (Dobos & Prazak, 2019, p. 222). The development of ADR capabilities by private companies can alleviate the dual-use concern. However, other confidence and trust-building measures might be required.

3.3 What is at stake?

In chapter 2, I gave a broad overview of the space environment, highlighting the increase in commercial activities and the overall number of operational spacecraft. Here, I dive deeper into the economics of space activities and space debris. Understanding the value of orbital space and the cost of space debris are key aspects when addressing the space debris problem. Some activities performed in space could not be performed on the ground or only at a significantly higher cost. At the same time, space debris increases the costs of conducting activities in space. In the near future, this cost could outweigh the benefits rendering some orbits unusable.

A common approach to assess policies consists of conducting a cost-benefit analysis of each approach available and selecting the one providing the largest net benefits. Using this approach in the space debris context requires knowledge of the benefits we get from the use of orbits and the cost incurred from space debris. Properly assessing remediation and mitigation approaches would require comparing the costs of conducting them to their benefits. For an ADR mission, it would require comparing the cost of removing the debris to the benefits from its removal (i.e., primarily the avoided cost of a potential collision). Unfortunately, data on the benefits of space activities and the costs of space debris are lacking. Moreover, the impact of the policy alternatives on those costs and benefits is difficult to model due to the long time scale involved and uncertainties on input parameters. In this section, I provide an overview of those costs and benefits and highlight the challenges in estimating them.

A first step in estimating the value of orbital space consists of looking at the space industry (§ 3.3.1). Its size, development, and benefits to society, give a broad view of what is at stake, and why orbital space should be preserved. However, this is only an imperfect proxy of the value of near-Earth space. We derive benefits from space that are not accounted for in the revenues of the space industry, especially through governmental space missions. Thus valuing orbits requires taking a broader approach (§ 3.3.2). Finally, one needs to address the present and future costs of space debris (§ 3.3.3). While it is difficult to assess their monetary value, listing the costs and the challenges in estimating their size is a first necessary step.

3.3.1 The space industry

The space industry value chain, depicted in Figure 3.1, is divided between upstream activities—manufacturing, launch, and the ground segment—and downstream activities—operations and services—with complementary activities such as insurance, regulations, and investment. Commercial satellite activities can be grouped into three main segments: Earth observations, satellite communications, and satellite navigation. Details of the revenues in 2018 from these three segments across the value chain are presented in Table 3.1. Most of the revenues (93%) come from the services provided by the satellite industry. Satellite communications (50%) and navigation (48%) represent the lion's share of the revenues, with Earth observations accounting only for 2% of the revenues. The total estimated revenue from the satellite industry in 2018 ranges from USD 277 B to 297 B, with a 5-year compound annual growth rate (CAGR) ranging between 4% and 7% (Euroconsult, 2019; Satellite Industry Association, 2019). On top of that, the non-satellite space industry, including governmental space budgets and commercial human space flights, amounted to USD 83 B. The Satellite Industry Association (2019) estimates that the US held on average 43% market shares of the global satellite industry over the years 2014–2018, with stronger growth than the rest of the world. It estimates that 217,341 people worked in the satellite industry in the US in Q3 2018. Euroconsult (2019) expects the revenues of the commercial satellite industry to reach USD 485 B by 2028. Reports by investment banks Morgan Stanley, Goldman Sachs, and Merrill Lynch predict revenues of USD 1 T or more in the 2040s (Foust, 2018).

3.3.2 The value of orbits

The space industry revenues give an idea of the value we derive from the use of orbital resources. However, it is a highly imperfect proxy. Numerous activities conducted in space are performed by governments and are thus not accounted for in the space industry revenues. Both military and civil satellites provide benefits to

3.3. What is at stake?

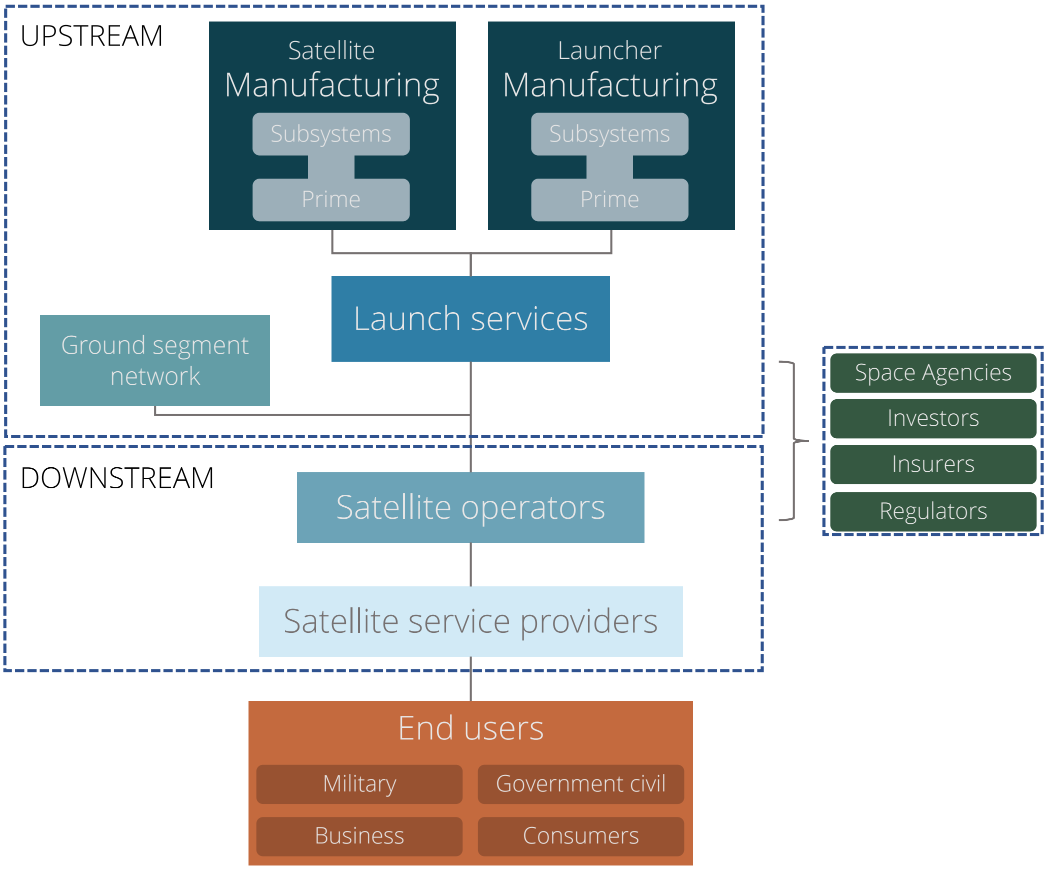

Figure 3.1 – The space industry value chain (adapted from Euroconsult, 2019).

Table 3.1 – Revenues across the three principal commercial value chains of satellite activities in 2018 in billion USD (Euroconsult, 2019).

	Satellite communication	Satellite navigation	Earth observation	Total	CAGR (5-years)
Manufacturing	3	0	0.5	3.5	4 %
Launch	1.2	0	0.1	1.3	5 %
Ground	2.9	0	0.04	2.94	4 %
Operations	12.1	0	1.5	13.6	−0.5 %
Services	124	148	3.4	275.4	8 %
Total	143.2	148	5.54	296.74	7 %

Note: Government systems enabling commercial services are omitted.

society, which are hard to measure. A prominent example is the European Earth observation program Copernicus, which provides data and information free-of-charge to anybody (Regulation (EU) 377/2014, 2014). The European Commission (2016, 2019) mandated PricewaterhouseCoopers (PwC) to study the socio-economic impacts and the user benefits of the program. Copernicus data is used in a wide variety of fields, including agriculture, forestry, urban monitoring, ocean monitoring, oil and gas, renewable energy, air quality, insurance, civil protection, and security. Using a conservative approach, PwC estimated that the Copernicus program generated, excluding non-monetary benefits, between EUR 16.3 B and 21.3 B between 2008 and 2020. The non-monetary benefits of Earth observations are difficult to measure but could be enormous. For example, better climate monitoring data could help take action and mitigate the disastrous effects of global warming. Although highly valuable, estimating the monetary value of this data is almost unfeasible. Evaluating the benefits from scientific research enabled by space missions (see, e.g., Bornmann, 2012; Cebr, 2019; A. J. Salter & Martin, 2001) or from national security provided by military satellites is also difficult. Greenblatt and Anzaldua (2019) list the space activities from which we are benefiting today and from which we will likely benefit in the next decades. In the current benefits, they list, among others, inspiration for STEM education, space spinoffs for Earth (i.e., technologies tested in or developed for space which find applications on Earth), and international space cooperation countering geopolitical tensions. All of these examples cannot easily be translated into monetary benefits and are not accounted for in the revenues of the space industry.

Esteve (2017) reviews the potential frameworks available to value orbital resources. He argues that the economic tools developed to estimate a monetary value for the environment could be applied in space. The latter is viewed as an "ecosystem" providing direct or indirect benefits to humankind (see, e.g., Costanza & Folke, 1997, for valuation of ecosystem services). Alteration of the ecosystem changes the services that it can provide. The management of an ecosystem requires making trade-offs across services and between time periods. Appropriately weighing those trade-offs requires some form of valuation (Farber et al., 2006).

The most common valuation methodology, labeled total economic value (TEV), takes an instrumental (usage-based) approach to value resources (Turner et al., 2001). The different components of the TEV are shown in Figure 3.2. On top of the commonly adopted use-value, this framework adds the option value and the non-use value. The use-value is either indirect when the value is derived from services provided by the ecosystem (e.g., prevention of downstream flooding), or direct when the interaction occurs with the ecosystem itself rather than the services it provides (e.g., harvesting of fish). The option value represents the price that individuals are willing to pay for the conservation of an element in view of

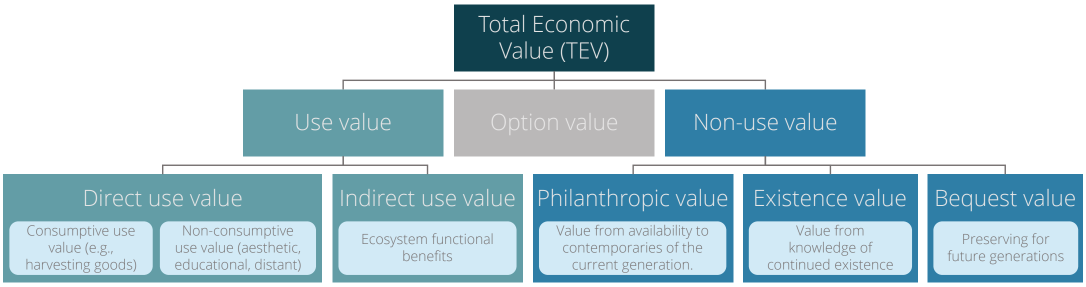

Figure 3.2 – Components of the total economic value (adapted from Turner et al., 2001).

its possible use in the future (Weisbrod, 1964). The non-use value represents the satisfaction that individuals derive from the knowledge of the existence of environmental resources (existence value), for the pleasure of others (philanthropic value), or for future generations (bequest value; Krutilla, 1967). In the TEV methodology, the three types of values—use, non-use, and option—are treated similarly and, when expressed in monetary terms, aggregated in a single dimension. However, such aggregation in a single measure of resource value is debated. Plottu and Plottu (2007, p. 52) argue that "option and non-use values stem from more different levels of choice problems than use values and thus, must be apprehended in a multidimensional framework." To the best of my knowledge, no attempt at eliciting non-use and option values for space have been conducted. The lack of data prevents a comprehensive use of the TEV methodology to orbital space.

3.3.3 The economic impacts of space debris

Deciding which mitigation or remediation measures should be taken in the space debris context requires evaluating the current and future costs caused by space debris. I look at the current economic impacts of space debris in § 3.3.3.1 and the futures ones in § 3.3.3.2.

3.3.3.1 Current economic impacts

Data on the current economic impacts of space debris is scarce. Whether private or governmental, operators do not communicate on the costs they incur in terms of shielding or debris avoidance maneuvers. In 2011, the National Research Council requested information on the cost of mitigation measures (including shielding, maneuvering, moving to a graveyard orbit, or taking other protective measures) but received only two estimates: the first was 0–10% and the second 5–10% of mission costs allocated to shielding and avoidance maneuvers. The information received suggested that “few experts see addressing orbital debris as imposing a large financial burden at present” (National Research Council, 2011, p. 92). Although this report suggested that “NASA, other space operational agencies, and the commercial space industry could consider keeping better track of debris-related costs” (National Research Council, 2011, p. 92), ten years later, no more data on space debris related costs are available to policy-makers. A recent OECD study on the topic only cites those rather old estimates without providing more up-to-date data (Undseth et al., 2020). From a policy perspective, there is a clear need to quantify the different costs associated with debris and mitigation measures.

In Table 3.2, I describe the current economic impacts related to space debris and the challenges in estimating their magnitude. The most prominent economic impact caused by space debris is losing an operational spacecraft following a collision with space debris (J. B. Taylor, 2011). Costs to build, launch, and maintain a spacecraft in LEO vary significantly between different applications. The Hubble Space Telescope, launched in 1990, is probably the most costly single satellite program in LEO. It costed USD 4.7 B at its launch (Ballhaus et al., 2010) and USD 9.6 B by its last servicing mission in 2009 (Overbye, 2009). In comparison, the reported manufacturing cost per OneWeb satellite was USD 1 M (Henry, 2019), and launch cost per satellite was USD 1.38–2.31 M (de Selding, 2015). When losing a satellite, not only the asset is lost, but also the value from the services derived from the data generated by the satellite. Efforts to mitigate the effect of space debris through the design of the spacecraft, the monitoring infrastructure, the operations, the clearance of orbits at EOL, and insurance are also significant costs.

Wiedemann et al. (2004) perform a cost-benefit analysis of various mitigation measures using parametric cost models and long-term simulations of the space debris environment. They show that passivation (suppression of explosions) and prevention of the generation of slag from solid rocket motors are the most cost-effective measures. Wiedemann et al. (2008) discuss the cost-effectiveness of shielding critical satellite components (not only to protect from space debris but also meteoroids). Ailor et al. (2010) derive the cost of maintaining complete constellations during twenty years. In their study, the economic impact of space debris is solely the cost to replenish the constellation due to lost satellites.

In their analysis of the costs space operators must consider when determining a debris-related response, Schaub et al. (2015) show that such costs vary strongly depending on the mission type. They summarize the strength for each mission type of direct and indirect costs, political costs, and cost to the space environment,

Table 3.2 – Current economic impacts of space debris (adapted from Undseth et al., 2020).

Type of cost/impact	Description	Challenge in cost estimation
Debris-related damages	Loss of functionality or loss of the entire satellite.	Damage due to untracked debris is not reported. Disentangling functionality loss due to debris impact from technical problems is difficult. Replacement cost underestimates the cost of satellite loss. The loss of service, customers, and reputation should be taken into account.
Satellite and constellation design	Costs associated with satellite shielding, collision avoidance and PMD capabilities, safehold modes, and redundancies (including spare satellites).	Design costs are not reported. Disentangling redundancies and safehold modes costs resulting from debris and technical issues mitigation is difficult.
Monitoring infrastructure	Cost of SSA and STM infrastructure, including sensors, tracking systems, and IT infrastructure (hardware and software).	Costs are born by public and private actors. The infrastructure is not solely used for debris mitigation but also for military purposes.
Operations	Costs of SSA and STM operational activities and services (including analysis and data management of conjunction warnings). Loss of service and fuel cost when conducting collision avoidance maneuvers. Launch delays and shorter launch windows.	Costs of SSA and STM operations are born by public and private actors. Private actors do not report the number and impact of collision avoidance maneuvers on their operations.
Orbit clearance	Cost of removing satellites from orbit at EOL (fuel and shorter lifespan). Fuel cost are relatively low in GEO (fuel for about three months of station-keeping) and high in LEO (above about 650 km altitude).	Revenue loss from a shorter lifespan is difficult to estimate. Fuel cost and cost for supplementary mass at launch can readily be estimated.
Insurance	In-orbit property insurance is bought by the majority of commercial operators and covers “all risks.” In-orbit third-party liability insurance is not often purchased and is a minor cost.	Insurance premiums do not disentangle risk from space debris and other risks (see discussion in § 6.3.2).

but do not provide numeric values. Currently, the direct cost of space debris is low because the perceived risk is too low to trigger active responses from operators. As the perceived risk increases, stricter mitigation measures will be taken (voluntarily or through regulation), which will create a set of recurring costs that will be difficult to reduce as stabilizing the debris population will require the continuation of those measures. Given the planned increase in space activities (see § 2.1), the high non-compliance rate with international guidelines (see § 4.2.3), and evidence from modeling (see § 2.2.4), stricter mitigation is unlikely to be sufficient to stabilize the space debris population. Once the perceived risk increases above a threshold, ADR will start to be implemented. However, the earlier ADR is implemented, the lower the costs for reducing the risk, as removing thousands of small fragments is significantly less cost-efficient than removing a large object (McKnight, 2010).

3.3.3.2 Future economic impacts

Economic impacts due to space debris are expected to rise sharply in the future (Undseth et al., 2020). As addressed in § 3.3.2, deriving the future value of orbits is difficult. Without this input, the future costs of space debris are uncertain. Table 3.3 summarizes the future economic impacts related to space debris and the challenges in estimating their magnitude.

The sooner the removal of space debris will be undertaken, the lower its cost will be. McKnight (2010, p. 1) observes that "it will always be at least an order of magnitude less expensive, quicker to execute, and operationally beneficial to remove mass from orbit as one large (several thousand kilograms) object rather than as the result of tens of thousands of fragments that would be produced from a catastrophic collision." This stems from the practicality of removing large objects rather than smaller ones. If the removal of large objects is undertaken soon enough to prevent catastrophic collisions, the retrieval of small fragments might not be required. However, if the population of smaller debris grows due to collisions, the retrieval of small objects might be necessary to keep the affected orbits usable.

3.3.4 Remediation costs

Apart from two satellites removed from orbit in 1984 during a space shuttle mission,[2] no objects have been actively removed from orbit. However, as mentioned in § 2.3,

[2]Astronauts manually captured the targets during spacewalks. The shuttle cargo bay was used to store the satellites to bring them back to Earth (see § 2.3).

Table 3.3 – Potential future economic impacts of space debris (adapted from Undseth et al., 2020).

	Type of cost/impact	Description	Challenge in cost estimation
Direct	Loss of unique capabilities and applications	Some orbits provide the best or the only source of data and signals in their domain (e.g., polar-orbiting weather and Earth observation satellites).	Estimating the added value of data obtained from a particular orbit compared to data obtained from other sub-optimal orbits or Earth is difficult. The same difficulty applies in valuing other space activities (e.g., communications, navigation).
	Loss or reduction of *new* capabilities and applications	New Earth observation and communication constellations are considered as a key driver of space activities and revenues in the coming decades but are threatened by space debris. Less risky terrestrial alternatives might be preferred.	Evaluating the impact of space debris on the economic viability of these new applications and the foregone benefits is difficult. There is high uncertainty on the viability of the business model proposed by megaconstellations.
	Human casualties	Human activities in space (e.g., the International Space Station) are threatened by space debris. Uncontrolled reentry of space debris could also result in human casualties.	There is high uncertainty on the level of human activities in LEO in the future.
	Orbit clearance	Removal of space debris (including payloads lost).	The cost of removing space debris is subject to high uncertainty, especially as which technology will prevail is unknown.
Indirect	Interrupted time series for Earth science and climate research	Uninterrupted time series are crucial for the accuracy and reliability of weather prediction and climate models.	The economic impact resulting from a loss of accuracy in climate and weather models is indirect with outcomes in the distant future, making it difficult to estimate.
	Distributional effects	The loss or perturbation of certain low-Earth orbits could be felt more heavily in rural low-density residential areas and low-income countries.	The extent to which rural areas and low-income countries are dependent on space infrastructure is unknown.

two missions to remove space debris are planned in the near future: ClearSpace-1 and CRD2. ClearSpace-1, which is aimed at removing a 120 kg piece of debris and is scheduled to launch in 2025, is budgeted at around EUR 120 M (e.g., Devlin, 2019; Hugo, 2020).[3] ESA member states have agreed to fund the first phase of the mission at the Space19+ Ministerial meeting (Perrin, 2019), strengthening this first price point. Only the first phase of CRD2 has been awarded, and no cost has been communicated.

The crewed 1984 NASA mission that retrieved two satellites placed into incorrect orbits relied on the space shuttle, which was extremely costly.[4] The absence of successful uncrewed demonstrative mission results in a high uncertainty on the costs of space debris remediation. The first successful debris removal will provide a first price point. Subsequent missions, especially if procured on a commercial basis, will provide the necessary price points to make predictions on the future price of space debris removal services. Two types of removal missions should be distinguished as they involve different capabilities and concepts of operations (CONOPS), resulting in very different costs. Missions aimed at removing single large pieces of debris (e.g., rocket upper stages) will require bespoke technology and CONOPS. In contrast, EOL services aimed at removing recently failed satellites (e.g., from constellations), potentially having grappling fixtures, will use more generic technology and CONOPS. The opportunity to remove multiple failures at once, as most constellation satellites have the same inclination, is instrumental in reducing the removal costs for EOL services. Due to the higher complexity inherent in removing large debris and the difficulty of removing multiple derelict objects at the same time,[5] those missions will have higher costs than EOL services.

Different mission scenarios and their flight dynamics trade-offs have been analyzed, enabling the derivation of propellant mass budgets (e.g., Castronuovo, 2011; T. Martin et al., 2013). A more comprehensive analysis of debris removal mission cost takes into account the development, manufacturing, launch, and operational costs. Braun et al. (2014) use a complete life cycle cost model and account for learning effects for single and multi-target missions. For single target missions aimed at removing the top priority objects, the cost of removing a kg of debris mass from orbit is about USD 70,000 for the first object and drops to about USD 30,000 for five objects removed and to about 20,000 after 15 objects (see their Figure 4). The significant research, development, test, and evaluation costs, which are

[3] This budget includes non-recurring engineering costs. Future missions are expected to be cheaper.

[4] According to NASA, the cost of the space shuttle averaged USD 450 M per mission (NASA, n.d.). However, the per-flight cost of the shuttle program could have been as high as USD 1.6 B (Wall, 2011).

[5] The likelihood to find multiple derelict targets in compatible orbits is low.

non-recurring, are spread on the different missions conducted. For multi-target missions, the cost is around USD 10,000 per kg when removing more than seven targets per mission. For two groups of debris targets, Yamamoto et al. (2017) perform a trade-off analysis of the ADR scenarios. Albeit using a cost model, they compare the scenarios relative to each other and do not provide any absolute value.

Requiring space operators to purchase EOL services for their failed satellites impose a cost on them. To assess the burden operators would face, I evaluate in Appendix C the cost per customer of such a requirement. If the per-customer cost is low enough, it can easily be passed on to customers without significantly affecting the company's profitability. I develop a simple model to estimate the per-user cost of EOL services for a OneWeb-like constellation.

3.4 Theoretical economic models

In Appendix D, I review in detail a small literature that address the issue of space debris and satellite launches using theoretical economic models. I summarize this review below.

Adilov et al. (2015) use a two-period model to show that competitive firms launch more satellites than the social optimum. Competitive firms do not take into account the negative externality their launches impose on others resulting in more launches and underinvestment in debris mitigation technologies than socially optimum. They compute the Pigouvian tax level that induces competitive firms to choose the socially optimum level of launches. In a subsequent paper, the same authors develop a dynamic model of space debris, which suggests the occurrence of an "economic" Kessler syndrome before the "physical" Kessler syndrome (Adilov et al., 2018). The increasing amount of orbital debris may render space economically unusable before it becomes physically unusable. In a static one-period model, Macauley (2015) derives numerical estimates of the externalities resulting from large and small debris generation and analyze the cost-effectiveness of different mitigation strategies. Acknowledging that Pigouvian taxes or cap-and-trade mechanisms can fully internalize the benefits from space debris mitigation and remediation but have limited institutional feasibility, Grzelka and Wagner (2019) investigate other policy measures that can incentivize firm to invest in mitigation and remediation. To move investment from the private to the social optimum, they suggest strengthening and clarifying intellectual property rights and promoting satellite debris take-back initiatives. Although insightful, their proposals seem to overestimate the benefits to firms of investing in remediation. More recently, Rao et al. (2020) showed, using a coupled physical-economic model, that introducing a tax on orbital use in 2020 would increase the net present value (NPV) of the satellite industry from around USD 600 B to around USD 3 T. In their model, introducing a tax on orbital use results in an immediate increase of the satellite industry NPV, which they trace to the reduction of launch activity when satellites and debris are suboptimally high. However, reducing launch today is unlikely to boost the satellite industry NPV instantaneously. The predicted optimal fee, which is in their model independent of the satellite and orbit characteristics, starts at USD 14,900 per satellite-year in 2020 and reaches around USD 235,000 per satellite-year in 2040. Their complex model relies on strong assumptions, e.g., regarding the development of the space economy, and shows relatively high discrepancies with historical values.

As the issue of space debris stems from a complex environment, with interactions between physical processes and satellite economics, its modeling requires simplifying assumptions. Albeit insightful, the interpretation and implications of the results provided by this body of work are limited by their strong assumptions.

4 Space governance

Global space governance is defined by Jakhu and Pelton (2017, p. 7) as "the entirety of the agreements, laws, regulations and other mechanisms (mandatory and voluntary) in relation to outer space affairs or activities, and includes processes for their formulation, compliance monitoring, and/or enforcement by concerned international and/or national institutions." This concept encompasses a wide range of instruments and institutions, including international treaties, national laws and regulations, guidelines, technical standards and procedures, and industry-gathered best practices (see Jakhu & Pelton, 2017, for a comprehensive overview of global space governance and its evolution). In this chapter, I focus my attention on space governance instruments and institutions most relevant to the space debris issue.

Space governance instruments can be divided into two categories (Oltrogge & Christensen, 2019): binding and non-binding (also referred to as soft law). International treaties, national laws, and regulations are binding instruments, while guidelines, code of conducts, and technical standards are non-binding. Although space debris is a global issue, the only international binding instruments governing space—United Nations (UN) outer space treaties—were drafted without the problem of space debris in mind. I briefly review the treaties relevant to the space debris problematic and their debated interpretation in § 4.1. After a prolific development of the international space law framework at the outset of the Space Age with the ratification of four UN outer space treaties, the space community transitioned to the development of voluntary guidelines (see Shackelford, 2014, who analyses the transition from a multilateral system centered on the UN to a polycentric regime complex). Albeit adopted on consensus, these guidelines are non-binding. However, these guidelines are often integrated into national space laws. I review the most important set of guidelines for space debris mitigation and space sustainability in § 4.2. Finally, I briefly describe the US regulatory landscape related to space debris in § 4.3.

4.1 Binding instruments

4.1.1 United Nations treaties

The main binding instruments of global space governance are five UN treaties drafted in the 1960s and 1970s (see Table 4.1 for an overview). As a product of their time, they are "state-centric" (von der Dunk, 2015). They were negotiated through the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS), a UN body created in 1958 which generally operates on consensus. Due to the compromises required to achieve consensus, "the language of the five treaties is not always clear and leaves room for varied interpretation" (Jakhu & Pelton, 2017, p. 21). The UN treaties are legally binding on the states who have signed and ratified them.[1] However, enforcement mechanisms are weak.

None of the UN treaties on outer space specify rules regarding space debris or even mention it. Nevertheless, two treaties impact the space debris problematic: the Outer Space Treaty (OST; 1966) and the Liability Convention (LC; 1971). To which extent the provisions of those treaties apply to space debris is subject to interpretation (see, e.g., H. A. Baker, 1989; Dennerley, 2018; Nelson, 2015).

4.1.1.1 The Outer Space Treaty

The Outer Space Treaty (OST; 1966) contains the core legal principles governing space activities. Although only the US and the Soviet Union had the capabilities to explore space when the treaty was drafted, there was a will among states to ensure that access and benefits from space accrued not only to those two countries (Jakhu & Pelton, 2017). Article I states that "[t]he exploration and use of outer space [...] shall be carried out for the benefit and in the interests of all countries" and that it "shall be the province of all mankind." The treaty guarantees the freedom of access, exploration, and scientific investigation of space. Although commercial activities were not prevalent when the treaty was drafted, Article VI ensures that states "bear international responsibility for national activities in outer space [...] whether such activities are carried on by governmental agencies or by non-governmental entities." Moreover, when conducted by non-governmental entities, space activities "shall require authorization and continuing supervision by the appropriate State"

[1] See Jakhu and Pelton (2017, "The Law of Treaties", p. 21) regarding the binding nature and enforcement of international treaties.

TABLE 4.1 – The five UN treaties on outer space. All the major space powers have ratified the first four UN space treaties, but not the Moon Agreement (UNOOSA, 2020).

Treaty	Full name	S	F	R
Outer Space Treaty	Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies	1967	1967	110
Rescue Agreement	Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space	1968	1968	98
Liability Convention	Convention on International Liability for Damage Caused by Space Objects	1972	1972	98
Registration Convention	Convention on Registration of Objects Launched into Outer Space	1975	1976	69
Moon Agreement	Agreement Governing the Activities of States on the Moon and Other Celestial Bodies	1979	1984	18

Note: S—Opened for signature; F—Entry into force; R—Number of states that have ratified the treaty, as of January 1, 2020.

(Article VI). States are not only responsible but also liable for the space activities conducted by non-governmental entities:

> "Each State Party to the Treaty that launches or procures the launching of an object into outer space [...] and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object or its component parts on the Earth, in air space or in outer space [...]" (Article VII).

The launch was chosen as the activity linking non-governmental space activities to states (as it is the easiest part of space activities to observe). The treaty also provides that states "shall retain jurisdiction and control" over objects launched into outer space (Article VIII), that states shall "conduct exploration of [outer space] so as to avoid [its] harmful contamination" and avoid activities which could lead to "potentially harmful interference with activities of other States" (Article IX).

Roberts (2000, p. 1124) observes: “Because [the OST] was drafted at a time when space activity meant rare and expensive government forays, little attention was paid to the possibility of pollution of the space environment. Instead the provisions of the treaty focused on ensuring freedom of access and forestalling the exercise of national control, not operational efficiencies. As a consequence, outer space itself was treated as a commons.” When the OST was drafted, space actors were unaware of the harmful impact space debris could one day cause. Only about ten years later, the seminal paper on the cascading effect space debris could engender was published (Kessler & Cour-Palais, 1978).

4.1.1.2 The Liability Convention

The Liability Convention (LC; 1971) clarifies the liability rules for damage caused by space objects mentioned in Article IX of the OST. It creates two separate liability regimes depending on where the damage occurs. The LC provides that a “launching State[2] shall be *absolutely* liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft in flight” (Article II). However, for in-orbit activities, it creates a fault-based liability regime:

> “In the event of damage being caused elsewhere than on the surface of the Earth to a space object of one launching State or to persons or property on board such a space object by a space object of another launching State, the latter shall be liable only if the damage is due to its fault or the fault of persons for whom it is responsible” (Article III).

The dispute settlement mechanism defined by the LC provides that first, a “claim for compensation for damage shall be presented to a launching State through diplomatic channels” (Article IX). If no settlement is reached through this channel within one year, “the parties concerned shall establish a Claims Commission at the request of either party” (Article XIV), which is a quasi-arbitral process (Nelson, 2015). Regarding damage suffered by private non-governmental entities, St. John (2012, p. 698) notes: “The Liability Convention is a tool for resolving international disputes. Consequently, as an international tool based on the Westphalian system,

[2]The Liability Convention (1971, Article I) defines a ‘launching State’ as “(i) A State which launches or procures the launching of a space object; (ii) A State from whose territory or facility a space object is launched.” Applying this definition to space missions of today, which often involve public and private cooperation, as well as the participation of actors from different countries at different steps of the missions, is challenging. See, e.g., Schrogl and Davies (2002), or Shakouri Hassanabadi (2014), for a discussion of the shortcomings of this definition.

only states may assert claims. Unique to space law, however, is that a state is responsible for 'national activities in outer space, regardless of whether ... those activities are conducted by government or private entities.' Therefore, an injured private entity must petition its government to make a claim on its behalf."

4.1.2 Uncertainties regarding liability for damage caused by space debris

Are launching states liable for damage caused by space debris? And if yes, in which circumstances? Article III of the LC provides that a launching state of a space object is liable for damage caused in-orbit by this object "due to its fault or the fault of persons for whom it is responsible." This leaves uncertainty as to how this provision would apply to space debris. I summarize the three major issues in applying the LC to space debris (Nelson, 2015):

1. *The meaning of "space object":* The LC states: "The term 'space object' includes component parts of a space object as well as its launch vehicle and parts thereof" (Article I). Does this definition encompass non-functional spacecraft, debris released during operations, and fragments resulting from collisions or explosions? While scholars seem to agree that intact but non-functional spacecraft are space object, the status of fragments remains unclear (see, e.g., H. A. Baker, 1989, p. 61–67).

2. *The fault-based regime:* The LC neither defines the fault nor establishes a standard of care for actors conducting space activities. Some argue that the internationally agreed guidelines on space debris (see § 4.2) establish the rules of conduct in space and can form the basis of a fault definition, but this point of view is debated (Nelson, 2015). Moreover, the guidelines would not be helpful in a variety of situations. If a fault standard were defined, the remote nature of space activities, which are difficult to monitor or inspect closely, would still render difficult the establishment of fault. "[F]or in-orbit damages, as the case of Cosmos-Iridium pointed out, identifying the liable state is relatively difficult because of the laboriousness of collecting objective data on the circumstances of the collision" (Degrange, 2018, p. 11). See Dennerley (2018) for a discussion on the interpretation of 'fault' in international space law.

3. *The definition of "damage":* The LC defines "damage" as "loss of life, personal injury or other impairment of health; or loss of or damage to property

> of States or of persons, natural or juridical, or property of international intergovernmental organizations" (Article I). It is unclear if "damage" extends to "costs of environmental remediation or of other injury that did not directly affect life or economic property" (Nelson, 2015, p. 121), and if it would cover, e.g., "lost revenue and profits or other damages that may be recovered under the U.S. or other national legal system" (Swiss Re, 2011, p. 24).

For a broader discussion on the uncertainties regarding liability for damage caused by space activities, see, e.g., H. A. Baker (1989), Kerrest and Thro (2016), or Nelson (2015).

4.1.3 Impediments to space debris remediation

As the UN outer space treaties have not been designed with space debris in mind, the removal of derelict objects faces some major legal obstacles. First of all, there is no universally accepted definition of space debris. Although internationally adopted space debris guidelines (see § 4.2) define space debris based on "non-functionality," these definitions are not legally binding. Second, Article VIII of the OST provides that states "shall retain jurisdiction and control" over objects launched into outer space, giving them perpetual sovereignty over the objects irrespective of their functionality status (Su, 2016). Tian (2018a, p. 120) argues that "Article VIII constitutes a serious legal obstacle that needs to be addressed for ADR to become a reality because it can give rise to an eventual denial, by the state with jurisdiction, of any effort to remove from orbit, space debris registered on its behalf, irrespective of its factual condition or situation." A. W. Salter (2016, p. 233) notes that securing consent to withdraw objects from a foreign nation might be difficult to secure because "much debris is valuable scrap material that is already in orbit." Escaping Earth's gravity well account for a large share of the cost of sending spacecraft in outer space. In the very long-term, there are plans to manufacture and recycle assets in space (see, e.g., Piskorz & Jones, 2018). Third, ADR requires complex orbital maneuvers and the movement of space objects, which increases the risk of collisions. The rendezvous and capture of space debris might result in the creation of new debris. ADR can thus trigger damage and subsequent liability (Tian, 2018a). Fourth, according to the LC (Articles II–III), a launching state is absolutely liable for damage caused by its space object on the surface of the Earth (or to aircraft in flight). However, if the damage occurs elsewhere than on Earth's surface, it is liable only if the damage is due to its fault or the fault of persons for whom it is responsible. Thus, de-orbiting an object can increase the liability risk as the object moves from the fault-based regime to the absolute liability regime. For a comprehensive discussion of the different legal aspects of ADR, see Froehlich (2018).

4.1.4 Avenues for legal recourse

The presentation of a claim for compensation for damage under the LC "shall not require the prior exhaustion of any local remedies" (Article XI.1). However, a state cannot present a claim under the LC "in respect of the same damage for which a claim is being pursued in the courts or administrative tribunals or agencies of a launching State" (Article XI.2). Thus, a private victim has two options to obtain compensation: "the dispute settlement mechanism under the liability convention or the recourse before a domestic judge under domestic law" (Kerrest & Thro, 2016, p. 68). However, the victim cannot pursue both the international and domestic track at the same time. For private operators, relying on the LC is a time-consuming process that involves petitioning the government to file a claim on their behalf. As the claim must initially be resolved through diplomatic channels, the state representing the victim might be unwilling to act or agree on partial compensation for political reasons (Kerrest & Thro, 2016). For these reasons, Kerrest and Thro (2016, p. 68) argue that "if the operator is solvent and the fault easy to prove, the claimant will, it is highly likely, choose domestic law." However, as we have seen, without a definition of fault, there cannot be an easy to prove fault. As highlighted by two concrete scenarios developed by Swiss Re (2011, 2018), the domestic track does not provide more certainty on the outcome. The absence of precedent in both the international and domestic track leaves the ability of a victim to recover its losses uncertain.[3]

4.2 Non-binding instruments

Since the adoption of the Moon agreement in 1979 (which has been ratified by only 18 states, none of which is a major space power), multilateral negotiations on a binding agreement under the auspices of the UNCOPUOS have failed. The lacunae in the binding space governance regime regarding space debris have been

[3]The LC has never been the cause of a contentious court case or arbitration. It was triggered once, in 1978, when a Russian nuclear-powered satellite Cosmos-954 crashed in Canada and spread radioactive debris. Canada billed CAD 6 M to the Soviet Union for the damage caused by Cosmos-954. After negotiations, the Soviet Union agreed to pay CAD 3 M (see, e.g., Jakhu & Pelton, 2017, p. 25).

addressed through non-binding instruments such as guidelines, technical standards, and industry-led best practices.

4.2.1 IADC and UNCOPUOS guidelines

The Inter-Agency Space Debris Coordination Committee (IADC), which is an international governmental forum consisting of the major national space agencies,[4] adopted the first international guidelines on space debris in 2002—later revised in 2007 (hereafter IADC Guidelines). They formed the basis of the Space Debris Mitigation Guidelines adopted by UNCOPUOS in 2007 and endorsed by the UN in 2008 (hereafter UNCOPUOS Guidelines, 2010). Both guidelines define space debris as "all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non functional." The IADC Guidelines cover the overall environmental impact of space missions and define two "protected regions with regard to the generation of space debris": the LEO region and the Geosynchronous region (see Figure 2.1). The guidelines have a focus on four areas:

1. Limitation of debris released during normal operations;
2. Minimization of the potential for on-orbit break-ups;
3. Post-mission disposal (PMD); and
4. Prevention of on-orbit collisions.

The UNCOPUOS Guidelines are similar to the IADC Guidelines. However, one major difference is that the IADC Guidelines recommend that the orbital lifetime of spacecraft or orbital stages, after completion of operations, should be limited to 25 years (hereafter 25-years rule), while the UNCOPUOS Guidelines do not.

Both sets of guidelines show the willingness to address space debris on the global stage but are limited in their reach (Su, 2016). First and foremost, they are not legally binding under international law. Second, they are not retrospective, i.e., they are applicable "to mission planning and the operation of newly designed spacecraft and orbital stages" (UNCOPUOS Guidelines), and existing ones "if possible" (UNCOPUOS Guidelines) or "to the greatest extent possible" (IADC Guidelines). Third, although military activities are responsible for a significant

[4] See https://www.iadc-home.org.

share of the debris population, these guidelines "do not seem to apply to security-related activities in outer space" (Su, 2016, p. 77).

In 2019, UNCOPUOS approved a set of 21 Guidelines for the Long-term Sustainability of Outer Space Activities (LTS Guidelines, 2019). These guidelines are high-level recommendations not only concerned with space debris. They provide guidance on four broad topics: (i) the national policy and regulatory frameworks for space activities; (ii) safety of space operations; (iii) international cooperation, capacity-building and awareness; and (iv) scientific and technical research and development.

These three sets of guidelines recommend states to implement them through relevant national mechanisms. The legal obligations provided by the UN outer space treaties to authorize and supervise space activities conducted by non-governmental entities, as well as their liability as a launching state, gave rise to national space legislation (see Froehlich & Seffinga, 2018, for an overview of national space legislation and the rationale for their enactment). The guidelines are often integrated as part of requirements in licensing procedures that are defined in the national space regulation or legislation.

4.2.2 Technical and industry standards

The IADC and UNCOPUOS Guidelines do not specify how the goals they set should be achieved. They have been completed by various technical standards developed by national space agencies, international organizations, and industrial consortiums or associations. The International Organization for Standardization (ISO) has developed a family of standards addressing debris mitigation. The ISO 24113:2019 is the top-level standard defining "the primary space debris mitigation requirements applicable to all elements of unmanned systems launched into, or passing through, near-Earth space, including launch vehicle orbital stages, operating spacecraft and any objects released as part of normal operations" (ISO, 2019). The European Code of Conduct for Space Debris Mitigation (2004), which has been adopted by the Italian, British, French, and German space agencies, as well as ESA, is consistent with IADC Guidelines but provides greater technical details and explanations. More recently, the Space Safety Coalition (2019), a group of satellite operators and other organizations,[5] has adopted a set of Best Practices for the Sustainability of Space Operations, which go beyond the internationally agreed

[5] The Best Practices of the Space Safety Coalition have been endorsed by 40 entities (as of May 28, 2020) including operators (e.g., SES, OneWeb, Iridium, Planet), manufacturers (e.g., Airbus), and insurers (e.g., AXA XL). See https://spacesafety.org.

guidelines. The Best Practices state, e.g., that “[s]pacecraft should strive for a disposal process providing a probability of successful disposal of 95%” (p. 11) and that “[o]perators of spacecraft that use chemical or electric propulsion to deorbit should strive to complete the deorbit phase within 5 years of end-of-mission” (p. 12).

4.2.3 Compliance with guidelines

More than 15 years after the adoption of the IADC Guidelines, analysis of the PMD of spacecraft show a low level of compliance with the 25-years rule. As presented in Figure 4.1, the level of compliance has increased over the years and reached about 85% for rocket bodies and 55% for payloads in 2018 and 2017, respectively. However, for non-naturally compliant objects, about 80% of the payloads do not even attempt to comply. Unfortunately, more detailed data on compliance with the guidelines is lacking. A fine-grained view on the space actors’ behavior would be helpful in both tailoring the policy response and incentivizing compliance with the guidelines.

4.3 Space debris regulation in the United States

The General Assembly of the UN and the UNCOPUOS recommend states to implement the internationally agreed space debris mitigation guidelines through relevant national mechanisms. I take the example of the US to highlight how space debris mitigation guidelines are incorporated at the national level (see Tian, 2018b, for a comprehensive discussion on the topic). Regulation and implementation of space activities in the US are divided among several government agencies:

1. The National Aeronautics and Space Administration (NASA) is the leading federal agency conducting research and development on aeronautics and space science and pursues the US civilian space program.
2. The Department of Defense (DoD) conducts activities in space in support of the military and develops space-based intelligence capabilities supporting US national interests.

3. The National Oceanic and Atmospheric Administration (NOAA), which is part of the Department of Commerce (DoC), conducts remote sensing activities and research on the Earth's environment and is responsible for licensing commercial remote sensing satellites.

4. The Federal Aviation Administration (FAA), which is part of the Department of Transportation, is responsible for issuing licenses for launch or reentry, or the operation of launch or reentry site, by US citizens anywhere in the world, or by any individual or entity within the US.

5. The Federal Communications Commission (FCC) regulates radio frequencies for telecommunications, broadcasting, and transmission by satellite.

NASA, the DoD, and NOAA are satellite operators subject to their internal rules regarding space debris. Moreover, the government-operated or procured space systems are subject to the US Government Orbital Debris Mitigation Standard Practices (ODMSP), which have been developed through an inter-agency working group and based on NASA safety standard. All commercial space activities are subject to space debris regulation by the FAA for launch and reentry. For in-orbit activities, commercial remote sensing satellites are subject to space debris regulations by the NOAA, while all satellites communicating with Earth are subject to the FCC's space debris regulations.[6] In the next chapter, I dive into the recent reform of the ODMSP and the current reform of the FCC's space debris mitigation rules.

[6]The FCC does not require a plan for post-mission disposal of remote sensing satellites when such a plan has already been reviewed and approved by NOAA.

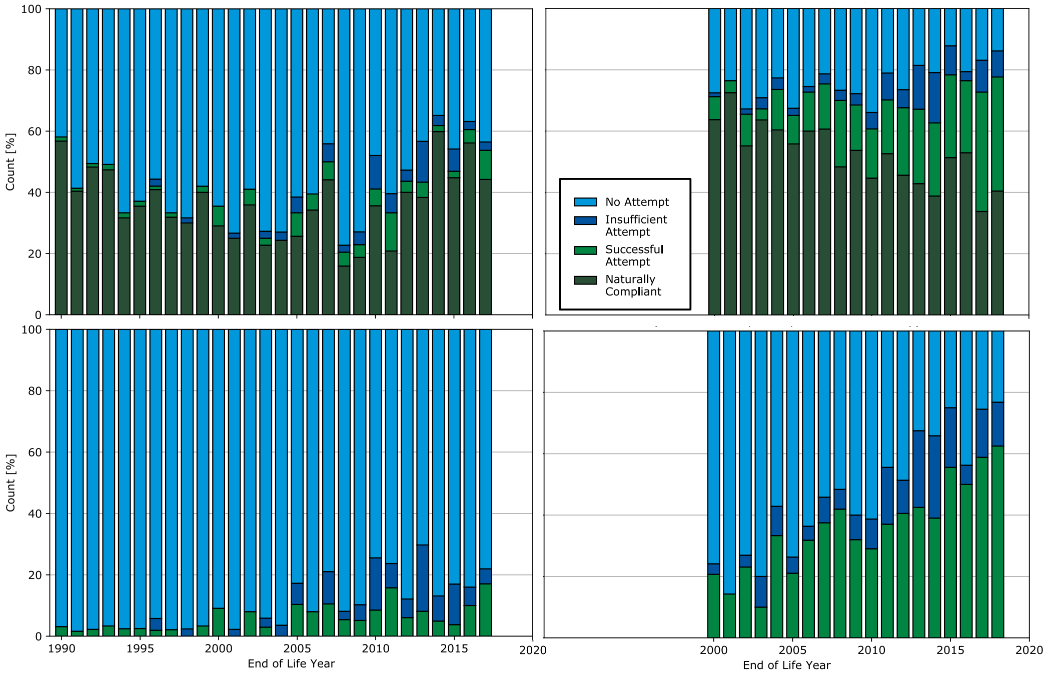

FIGURE 4.1 – End-of-life compliance with the 25-years rule in LEO (taken from ESA Space Debris Office, 2019, p. 63–64). Relative clearance in terms of numbers. *Left column:* payloads. *Right column:* Rocket bodies. *Top row*: All objects. *Bottom row:* Excludes naturally compliant objects.

Note: Naturally Compliant—Injected into an orbit that fulfills the 25 year lifetime measure; Successful Attempt—Compliant after an attempt to reduce the object's orbital lifetime or re-orbit above LEO; Insufficient Attempt—Not compliant but having attempted to reduce the object's orbital lifetime or re-orbit above LEO; No Attempt—Not compliant with no attempt at all.

5 Space policy reforms in the United States

The promises of a new space era that brings economic prosperity and innovation to the United States (US) has pushed the current administration to place a greater emphasis on space policy than the previous one. The Trump administration developed the first National Space Strategy (NSS, 2018) aimed at putting America's interests in space first. The whole strategy is aimed at accelerating human exploration of space, strengthening US space defense capabilities, and developing new economic opportunities. The revival of the National Space Council and the signing of four space policy directives by President Trump highlight this regain of interest for space in the US government. The overarching policy goals of the current administration constrain and shape the policies specific to orbital debris mitigation and remediation that can and will be enacted.

With its NSS, the administration wants to prioritize "American interests first and foremost" with a strategy "that will make America strong, competitive, and great" (NSS, 2018). To this end, the US wants to "partner with the commercial sector to ensure that American companies remain world leaders in space technology" and prioritize "regulatory reforms that will unshackle American industry and ensure [it] remain[s] the leading global provider of space services and technology" (NSS, 2018). At the same time, the strategy calls for "strengthening the safety, stability, and sustainability of [the US] space activities" (NSS, 2018). The NSS is based on four pillars. While the two first pillars are focused on US space defense capabilities, deterrence, and warfighting options, the two last are more closely related to orbital debris. The third pillar is aimed at improving "foundational capabilities, structures, and processes" to ensure "effective space operations through improved situational awareness, intelligence, and acquisition processes" (NSS, 2018). The fourth pillar is aimed at fostering "conducive domestic and international environments [by] streamlin[ing] regulatory frameworks, policies, and processes to better leverage and support U.S. commercial industry" (NSS, 2018). The NSS is focused on national defense and fostering the commercial use of space with only a brief mention of space sustainability. Its two last pillars will shape and constrain which space debris policy reform will be developed. Short-term commercial interests and sustainability goals do not always go together, and the overall direction set by the administration could, in some areas, tip the scale on one side or the other.

In this chapter, I first look at two of the Space Policy Directives enacted by President Trump that target regulation of commercial space and Space Traffic Management (STM), as both subjects are of high relevance for mitigating orbital debris (§ 5.1). I then describe the November 2019 update of the Orbital Debris Mitigation Standard Practices (ODMSP), which apply to all US Government satellite operators (§ 5.2), and a policy reform by the Federal Communications Commission (FCC) regarding orbital debris mitigation for the licensing of commercial satellites (§ 5.3). Given the reach of the FCC and the in-depth revamping of the rules attempted, this policy reform could be a milestone in orbital debris mitigation. I use this concrete example to assess the different command-and-control rules that can be applied in the space debris context. I look in detail at the comments filed by interested parties regarding the rules proposed by the FCC (§ 5.4). Their analysis enables a better understanding of the stakeholders' position and their level of agreement regarding potential new rules for space debris mitigation. Finally, I discuss the FCC decision to enact some of the proposed rules and postpone others for further comment (§ 5.5).

5.1 Space Policy Directives

5.1.1 Space Policy Directive-2: Streamlining regulations on commercial use of space

The Space Policy Directive-2 (SPD-2, 2018), a presidential memorandum signed by President Trump on May 24, 2018, is intended at streamlining regulations on commercial use of space. The overarching goal of the document is to make sure that "regulations adopted and enforced by the executive branch promote economic growth; minimize uncertainty for taxpayers, investors, and private industry; protect national security, public-safety, and foreign policy interests; and encourage American leadership in space commerce" (SPD-2, 2018). Accordingly, the Directive mandates the reviewing of launch and reentry licensing, commercial remote sensing, radio frequency spectrum, and export licensing regulations to ensure that they are consistent with the above-mentioned policy.

The goal of this Directive is to push the different agencies responsible for space activities to clarify and simplify their regulatory process, or even remove restrictions, to promote the development of space activities and help foster US dominance in the global space industry. Although a clearer and more unified regulatory framework is a necessary building block for sustainable space, the streamlining of regulations would probably result in less effective rules. Enacting more stringent requirements for space debris mitigation would contradict with the overarching goal of SPD-2.

5.1.2 Space Policy Directive-3: National space traffic management policy

The Space Policy Directive-3 (SPD-3, 2018) is a presidential memorandum, signed by President Trump, on June 18, 2018. The document acknowledges that congestion and contention in space are increasing, which "presents challenges for the safety, stability, and sustainability of U.S. space operations" (SPD-3, 2018). The US capabilities to respond to these new challenges are not adequate: the DoD will not be able to track an increasing number of space objects (due to more launches and more sensitive sensors), and the STM capabilities are limited. The current architecture is not adapted to the diversity of future activities in space such as satellite servicing, ADR, in-space manufacturing, tourism, and very large constellations. The document recognizes that maintaining US leadership in space requires the development of strong Space Situational Awareness (SSA)[1] and STM[2] capabilities. The development of both capabilities is necessary to enable a "safe, stable, and operationally sustainable space environment" (SPD-3, 2018). In SPD-3, President Trump shifts the responsibilities for STM and SSA from the DoD to the DoC and mandates the provision of some basic free SSA and STM services.

Regarding orbital debris, SPD-3 recognizes that "[d]ebris mitigation guidelines, standards, and policies should be revised periodically, enforced domestically, and adopted internationally to mitigate the operational effects of orbital debris" (SPD-3, 2018). Three key requirements are identified: the guidelines and practices need to be updated; the update must enable more efficient and effective compliance to the rules; the new standard should permit their international adoption. The latter shows the US's willingness to set the standard nationally and then drive its

[1]SPD-3 (2018) defines SSA as: "the knowledge and characterization of space objects and their operational environment to support safe, stable, and sustainable space activities."

[2]SPD-3 (2018) defines STM as: "the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment."

international adoption.

Acknowledging that the US ODMSP are outdated and inadequate to control the growth of orbital debris, SPD-3 asks NASA[3] to update them and establish new guidelines for satellite design and operation (see § 5.2). In the longer term, SPD-3 recommends the incorporation of appropriate standards and best practices into Federal Law and regulation. The document also states that the US should "pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes"(SPD-3, 2018).

5.2 Update of the Orbital Debris Mitigation Standard Practices

Adopted in 2001, the US Government Orbital Debris Mitigation Standard Practices (ODMSP) have been, as mandated by SPD-3 (see § 5.1.2), updated in November 2019. These standard practices apply to US Government operators, which include NASA, NOAA, and the DoD, and must be embedded in regulation for commercial space activities.[4]

The major change in the ODMSP is the inclusion of metrics that identify quantifiable goals that operators must meet. Regarding collision risks, the ODMSP require that operators limit to less than 0.001 the probability of collision with objects 10 cm and larger during orbital lifetime, and to less than 0.01 the probability that collisions with micrometeoroids and orbital debris smaller than 1 cm will cause damage that prevents post-mission disposal (PMD). For PMD, the updated ODMSP require that its probability of success be no less than 0.9 with a goal of 0.99 or better. The update also added a metric on the debris released during normal operations, expanded the options available for PMD, and introduced special practices for some class of operations such as small satellites, large constellations, or proximity operations.

The space safety community welcomed the changes with limited enthusiasm, as it felt that the update failed to take into account the ongoing changes in the space sector (Foust, 2019; B. C. Weeden, 2020; C. Weeden, 2020). The non-reduction of the 25-years post-mission lifetime and the lack of a more stringent PMD reliability

[3] NASA is responsible for leading an interagency working group which comprises the Secretaries of State, Defense, Commerce, and Transportation, and the Director of National Intelligence, with the FCC in a consulting role.

[4] The FAA, the FCC, and NOAA regulate commercial space activities (see § 4.3).

requirement for large constellations have been especially pointed out. There is growing consensus in the private sector that those rules will not be sufficient to safeguard the space environment, as can be seen from the recent foundation of the Space Safety Coalition, which, among other things, advocates for a 5-years post-mission lifetime (see § 4.2.2).

5.3 Notice of proposed rulemaking: Mitigation of orbital debris in the new space age

The Federal Communications Commission (hereafter FCC or the Commission) is considering amending its licensing rules regarding orbital debris. In November 2018, the Commission launched a Notice of Proposed Rulemaking (hereafter NPRM or Notice) entitled "Mitigation of Orbital Debris in the New Space Age" to review its rules adopted in 2004. In this document, the Commission acknowledges that "we are at a turning point in the history of space development" (NPRM, 2018, p. 2) and that the thriving new space economy (e.g., the proposed megaconstellations) is presenting challenges to the sustainability of the space environment which must be addressed by establishing new rules.

In the NRPM, the FCC is proposing "changes [...] designed to improve and clarify [the] rules based on experience gained in the satellite licensing process and on improvements in mitigation guidelines and practices, and to address the various market developments" (NPRM, 2018, p. 3). The Commission proposes explicit amendment of title 47 of the Code of Federal Regulations (47 C.F.R.) on Experimental Radio Service (2015, 47 C.F.R. §5), on Satellite Communications (2010, 47 C.F.R. §25), and on Amateur Radio Service (1996, 47 C.F.R. §97). Along theses proposed new rules, the FCC seeks comment on various aspect of space debris mitigation which includes control of debris released during normal operations, minimizing debris generated by the release of persistent liquids, safe flight profiles, PMD, proximity operations, operational rules, liability issues, and economic incentives. The previous version of the rules gave "some general guidance on the content of disclosures, but the Commission generally declined to adopt a particular methodology for the preparation and evaluation of an applicant's orbital debris mitigation plans" (NPRM, 2018, p. 4). In this NPRM, the FCC proposes the inclusion of more specific design or operational requirements, especially the inclusion of metrics to assess various aspects of the applicants' orbital debris mitigation plans.

The NRPM was published in the Federal Register on February 19, 2019. From this date, interested parties had 45 and 75 days to file comments and reply comments, respectively. This comprehensive review of orbital debris mitigation rules with comments from interested parties offers an opportunity to get a deeper understanding of stakeholders' positions, expectations, and mindset. The commentators' assessment of the propositions gives information about their feasibility and their perceived efficiency and effectiveness. In § 5.4, I attempt at rigorously analyzing the comments and reply comments to the NPRM. After analysis of the comments and industry calls for postponing the adoption of the proposed rules (e.g., AIA Comment, 2020; SIA Ex Parte Presentation, 2020), the FCC released a Report and Order and Further Notice of Proposed Rulemaking (R&O and FNPRM, 2020) on April 23, 2020. The Commission decided to only adopt a limited set of rules and asks further comments on the debated rules and new propositions through a FNPRM. I discuss this decision in § 5.5.

5.4 Analysis of stakeholders' positions regarding the new orbital debris rules proposed by the FCC

The NPRM "Mitigation of Orbital Debris in the New Space Age" has received 50 comments and 16 reply comments from 53 different parties. To simplify the analysis, I consider only one document per party. For the 13 parties which have filed both a comment and a reply comment, only the comment is considered, while for the three parties that only filed a reply comment, those will be referred to as comment in the following analysis. The diverse set of actors that filed comments to the Notice is presented in the left panel of Figure 5.1. Companies represent more than half of the comments filed. Due to the low awareness level of space debris in the general public and the rather technical level of the regulation discussed, the number of individuals commenting on the NPRM is low. In the right panel of Figure 5.1, the sector of activities of the 28 companies is shown.

In this analysis, I focus on rules for non-geostationary satellite orbits (NGSO) and ignore points related to geostationary satellite orbits (GSO).[5] I also focus on rules for commercial satellites and thus exclude three comments which are identified as

[5] I do not discuss rules specific to GSO systems as the focus of the NPRM is on NGSO, and the space debris issue is the strongest in LEO (see chapter 2).

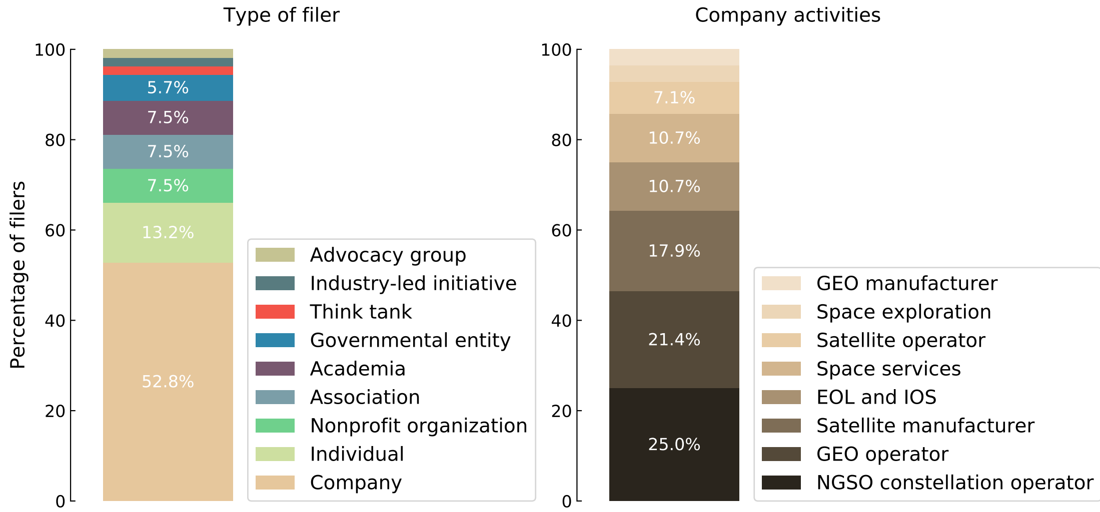

FIGURE 5.1 – *Left panel:* Distribution by types of the 53 different parties which filed a comment or reply comment to the NPRM "Mitigation of Orbital Debris in the New Space Age." *Right panel:* Distribution by sector of activities of the 28 companies that filed a comment or reply comment.

only related to 47 C.F.R. §97 on Amateur Radio Service (1996).[6] This leaves 50 comments on the NPRM for analysis. I first look at general aspects addressed in the comments and make qualitative comparisons between them. This approach helps grasp the filers' general mindset and their positions regarding the FCC's approach regarding space debris mitigation. In a second step, I focus on selected narrow propositions of the FCC and attempt to make a quantitative comparison of stakeholders' positions. The selection of propositions for quantitative analysis is based on three criteria: the proposition had to involve a clear and specific requirement, be potentially critical for preserving the space environment, and be addressed by more than a few filers. Proposals that lay more in the field of SSA and STM were excluded. Table 5.1 presents the 15 items selected along with the share of agreement by the 50 commentators. Most of the comments address the NPRM broadly and do not address the propositions in detail. The most addressed proposition of the 15 selected is commented only by 36% of the filers. The comments on the selected propositions have been coded manually into four categories: for, against, no clear-cut position, and not mentioned.[7]

[6]Note that 47 C.F.R. §5 on Experimental Radio Service (2015) includes, for example, product development and market trials, and is thus not excluded from the analysis.

[7]When a filer advocates for a more stringent requirement than the proposition, I code its comment as supporting the proposition. Moreover, if the filer quotes someone or some entity supporting a proposition without further comment, I assume the filer endorses the proposition.

TABLE 5.1 – Overview of stakeholders' position on 15 selected items of the FCC's NPRM (2018) on space debris mitigation and their adoption by the FCC (R&O and FNPRM, 2020).

		F	A	NP	NM	AD
Safe flight profile	Collision probability with large objects not greater than 0.001 (§26)	18%	6%	4%	72%	✓
	Large objects metric applied on an aggregate basis (§26)	10%	14%	4%	72%	→
	Collision probability with small objects not greater than 0.01 (§27)	12%	6%	2%	80%	✓
	Small objects metric applied on an aggregate basis (§27)	8%	12%	4%	76%	→
	Specification of reasons why a particular orbit is chosen if above 650 km (§31)	4%	10%	2%	84%	✗
	Propulsive capabilities required for stationkeeping above particular altitude (§34)	8%	22%	4%	66%	→
	Maximum limit for variance in orbit for NGSO systems (§35)	6%	10%	6%	78%	✗
	Design and fabrication reliability requirement if above altitude threshold or large system (§43)	2%	26%	4%	68%	✗
Post-mission disposal	Probability of PMD success larger than 0.9 (§46)	16%	2%	4%	78%	✓
	PMD metric applied on an aggregate basis (§46)	2%	10%	6%	82%	✗
	Initial deployment below 650 km and orbit raising with full functionality (§48)	2%	18%	4%	76%	✗
	Require to include automatic disposal by a de-orbiting device (§50)	6%	16%	0%	78%	✗
	Reduction of 25-years rule (§59)	28%	8%	0%	64%	→
Liability & scope of rules	Indemnification of the US for any costs associated with a claim (§78)	2%	24%	4%	70%	→
	Rules also applied to non-US-licensed satellites seeking market access (§85)	18%	0%	8%	74%	✓

Note: Paragraphs in parenthesis refer to the NPRM. 50 responses to the NPRM are considered. F—For; A—Against; NP—No clear-cut position; NM—Not mentioned; AD—Adopted in the R&0 of April 23, 2020 (R&O and FNPRM, 2020); →—Moved to the FNPRM.

5.4.1 General points addressed in the comments

5.4.1.1 FCC's authority to regulate space debris

In the Notice, the FCC acknowledges "a shared a role with other agencies in evaluating orbital debris mitigation plans associated with non-Federal space operations" (NPRM, 2018, p. 7) and questions its legal authority to adopt the rules proposed in the Notice. In its statement regarding the Notice, Commissioner Brendan Carr asks: "Are we the expert agency to make these assessments?" and "What are the right agencies and experts to answers these questions? Should the FCC be one of the lead agencies? Should we play a supporting and coordinating role instead?" (NPRM, 2018, p. 61–62).

A large number of commentators address these questions. Most of them do not comment on the Commission's authority to regulate but enjoin it to cooperate more closely with other agencies and internationally. OneWeb (2019, p. 2) notes that "the discussion—and resolution—of these complex issues must involve many more stakeholders and government bodies, both domestic and international" and Maxar (2019, p. 3) advocates for a "holistic review of orbital debris policies across all federal agencies with responsibilities for authorizing and licensing commercial space activities." Commentators are concerned about duplicative or inconsistent regulatory requirements. They would welcome a comprehensive review of jurisdiction, capabilities, and available resources of the different agencies to allocate roles and responsibilities regarding space debris mitigation efficiently. The members of the Consortium for Execution of Rendezvous and Servicing Operations[8] (2019, p. 3) would prefer the "consolidati[on of] the orbital debris mitigation guidelines into a single framework under a single agency" which would apply the requirements equally across all US private-sector space activities. The Secure World Foundation (2019) agrees and adds that such an entity should also be responsible for the civil SSA mission as both tasks are complementary.

The Commission mentions in the Notice that its jurisdictional authority over space activities is dependent on the assessment that its actions serve the public interest. In its comment, the U.S. Department of Commerce (2019, p. 2–3) notes that such assessment must integrate "the President's policies on space commerce and the corresponding expertise, initiatives, and rulemakings of the federal agencies tasked by the President in the Space Policy Directives with carrying out those policies." The DoC enjoins the FCC's actions to "reflect the President's approach to regulation of space to advance responsible, safe U.S. innovation and investment."

[8] An industry-led initiative.

To coordinate the President's actions and reforms undergoing in other agencies, the DoC "respectfully requests that the Commission defer action in this proceeding until completion of the agency actions mandated by the President's Space Policy Directives" and "requests the Commission's participation in an Interagency Working Group on Commercial Orbital Debris Requirements to, among other things, identify the proper agency to administer orbital debris regulations."

Although the discussion regarding which agency should be responsible for developing and enforcing a comprehensive orbital debris mitigation framework is necessary, the Secure World Foundation (2019, p. 3) argues that at the moment, "it is appropriate for the FCC to continue to include orbital debris mitigation requirements in its licensing of satellite systems as it has the broadest reach of any of the existing U.S. regulatory agencies for space." Without the Commission undertaking this task, some space activities would not have the appropriate regulatory oversight regarding orbital debris.

I do not dig deeper into the regulatory architecture that would yield the most consistent and efficient orbital debris mitigation framework and focus more on the propositions made by the FCC.

5.4.1.2 Disclosure requirements without guidance on how the information is used

Some of the disclosure requirements proposed in the Notice are not directly tied to a threshold or an assessment method. Some of the commentators perceive negatively such disclosure obligations without guidance on how the Commission will use the information. The disclosure of why a particular orbit has been chosen, which is discussed in further detail in § 5.4.2.2, is an example of such an informational requirement without a clear assessment rule. Boeing (2019, p. ii), for example, states: "[t]he Commission should also refrain from adopting any additional orbital debris rules that require satellite license applicants to disclose information to the Commission regarding the planned operations of their satellite systems without concurrently providing objective guidance regarding the manner in which such information will be assessed by the Commission staff and how they will determine which operations and numeric values are presumptively acceptable."

Although this approach leaves regulatory discretion to the Commission and allows for fine-tuning its decision to the evolution of the space environment, it lacks predictability and certainty. This uncertainty is a risk for operators that are entirely dependent on the grant of a license for their systems to run their business.

This increased risk might deter investments in innovative new ventures and reduce investments at large. By not providing the methodology by which a piece of information is assessed, the Commission can perform a differential treatment of the applicants. While this enables the Commission to adapt its decision to particular situations or take into account the applicant's compliance history, it runs the risk of providing an unequal treatment of applicants.

5.4.1.3 Performance-based requirements instead of technical requirements

Most of the companies that have filed a comment to the NPRM have expressed their concerns regarding the flexibility of one or some of the proposed rules and the constraints on innovations that might result from them. According to them, the Commission should regulate on narrowly-defined key aspects using performance-based indicators rather than mandating any specific technology. SpaceX (2019, p. 3), for example, believes that "[a]ny rules should rely on verifiable and enforceable performance metrics rather than unnecessarily prescriptive or specific technology requirements," in other words "the government should define what needs to be accomplished, rather than prescribing how these goals must be achieved in any given situation." Such an approach should enable the private sector to develop cost-effective solutions to meet the performance requirements and be flexible enough to adapt to rapidly-evolving space activities.

5.4.1.4 The need for international cooperation and the risk of forum shopping

Commentators are cognizant of the international nature of the orbital debris problem. They urge the Commission and the US government to undertake international discussions to harmonize the requirements. SpaceX (2019, p. ii) notes that "no efforts to safeguard space will be effective unless they are applied broadly and adopted internationally," but is aware that by having the power of granting US market access to non-US-licensed operators, the FCC can affect the broader space environment. I discuss this aspect further in § 5.4.5. Lockheed Martin (2019, p. 4) while supporting that "only with a concerted effort the long-term sustainability of the globally-shared space domain for U.S. space system operators and all others will be ensured," perceives that the American leadership on this matter "with other spacefaring nations and their stakeholders' 'buy-in' to a US-led approach" could be a path to success.

5.4.1.5 The pressing need for remediation

Three commentators recognize that regulations to mitigate the impact of future launches might not be sufficient to solve the orbital debris problem. The Commercial Smallsat Spectrum Management Association (2019, p. 4) notes that "the removal of existing debris in orbit is critical to maintaining a safe and sustainable orbital environment." At the same time, McKnight (2018, p. 1) argues that we should also focus on "managing the non-operational massive derelicts in LEO that pose the greatest debris-generating potential now and in the future." To address this problem, McKnight advocates for pursuing ADR and JCA, but without providing a pathway to the development and implementation of these technologies. The Secure World Foundation (2019, p. 8) stresses that economic incentives can play a limited role in dealing with the accumulation of orbital debris, as the highly-congested regions of space are the result of governmental activities and are still primarily used by governments for public services. The Foundation thinks that "[e]conomic incentives are likely a useful tool for encouraging responsible private sector behavior in the future, and thus reducing the creation of or motivating the removal of future orbital debris, but are unlikely to be a useful tool to fund cleanup of existing orbital debris" and believes that "removal of the existing orbital debris will need to be funded by governments as they are the primary source of current orbital debris." To enable the clean up of existing orbital debris, the Foundation proposes the use of a "government-supported technology development program, coupled with government purchase of service contracts."

5.4.1.6 Beyond the Earth's gravity well

Only a few commentators underline that the rules proposed by the FCC are only intended for Earth-bound orbits. The Commission refers to GSO and NGSO to qualify orbits, but it is not clear if orbits around other celestial bodies qualify as NGSO. Some of the rules to be applied to NGSO do not seem well suited for other celestial bodies. The Global NewSpace Operators[9] (2019, p. 22–23) estimate that "it is time to start a discussion on how any debris mitigation rules should apply to lunar orbit" and point out that "no organization independently track[s] all lunar spacecraft."

When UN outer space treaties were drafted, space debris was not yet recognized as a threat to the sustainable use of space (see § 4.1). It resulted in international

[9] Group of companies which defines itself as comprising "emerging orbital operators, spaceflight safety experts, manufactur[ers] and suppliers, and engineering services, [that] all have a stake in furthering spaceflight safety by mitigating the creation of orbital debris" and includes Astroscale.

regulations not suited to deal with the space debris problem. Commercial activities around other celestial bodies than Earth are foreseeable, and thus proper regulation should be put in place before those activities become common. To avoid repeating the mistakes of the past and encourage good behavior from the start of commercial activities elsewhere than around Earth, regulations should encompass those activities.

5.4.2 Safe flight profile

5.4.2.1 Quantifying collision risk

The FCC's current rules require "an assessment of the probability of a satellite becoming a source of debris as a result of a collision with a large debris, but do not require that the operator quantify this probability" (NPRM, 2018, p. 10). In the NPRM, the Commission proposes to require applicants, based on the current NASA standard, to demonstrate that the collision probability with a large object[10] over the lifetime of their spacecraft will be no greater than 0.001. The Commission also proposes to incorporate the NASA standard regarding collision probability with small debris. With this rule, applicants would have to certify that over the lifetime of their spacecraft, the probability of collision with a small object that would cause loss of control and prevent PMD is less than 0.01. For both collision probability metrics, the FCC seeks comment on whether it should be applied on a per-satellite basis or in the aggregate.

Respondents generally agree (18% for; 6% against; see Table 5.1) with the requirement for operators to demonstrate that the collision probability over the lifetime of their spacecraft will be no greater than 0.001. Three operators—Intelsat, SpaceX, and Swarm—are not convinced by this requirement. Their concern is more related to the difficulties in measuring these probabilities, the inability for the Commission to verify the metrics, and the risk that models will be tweaked by operators to find results matching their interests. SpaceX (2019, p. 17) notes that "[w]hile well-intended, these types of metrics simply are not verifiable by the Commission—or in certain circumstances even by the spacecraft operators themselves—in advance of launch" and that "establishing such a threshold could invite technical compliance through fine-tuning of a computer model, rather than investment in technology and more scrutiny of real-world operational characteristics." McKnight (2018, p. 1) also underlines that the document "underestimate[s] the difficulty in actually calculating

[10]The definition of "large object" is discussed in the NPRM and in the comments, but is not addressed in this work.

the probability of collision in a repeatable and mutually-verifiable approach." Other respondents recognize the limitations of modeling but advocate for its advantages in assessing risks. For example, Orbcomm (2019, p. 11) states: "Although the limits of any attempts to model collision risk with a truly dispositive degree of accuracy must be recognized, modeling unquestionably does serve as a necessary means of identifying potentially risky proposals."

The second collision metric proposed by the Commission is intended to limit the risk of a satellite being unable to perform its PMD. The level of agreement (12% for; 6% against; see Table 5.1) for this proposition seems lower than for the large objects collision metric. However, three respondents' above-mentioned concerns remain the same for this metric, while fewer respondents have commented on this proposition. As the aim of this metric is to prevent the satellites from becoming debris due to loss of control and inability to perform PMD maneuvers, OneWeb proposes to use a more holistic approach than a metric assessing the risk of collision from small debris. Indeed, OneWeb (2019, p. 18) argues that "small debris impacts represent only one contributor to the overall risk of being unable to de-orbit" and advocates for "the adoption of a comprehensive deorbit reliability metric (accounting for all failure modes)."

There is not much discussion around the level of these two metrics and on what basis they have been derived. The respondents do not question NASA's authority regarding theses standards. Telesat (2019, p. 3), however, "suggests that the metrics should be pro-rated based on a 5 year service life." It argues that when the standard was developed, the expected LEO satellite mission lifetime was five years. Thus the metric should take this into account to avoid incentivizing shorter missions.

The debate whether those two metrics should be applied on a per-spacecraft basis or in the aggregate is fierce (10% for and 14% against for the large debris metric; 8% for and 12% against for the small debris metric; see Table 5.1). All of the companies, which have requested a license for a large constellation,[11] except OneWeb, advocate for the application of these metrics on a per-satellite basis. Telesat (2019, p. 3) is concerned that the "[a]pplication of these metrics on an aggregate or system-wide basis would artificially cap constellation size and hamstring the ability of LEOs to provide continuous high capacity global coverage." At the same time, Amazon (2019, p. 2) underlines that applying the metrics "on an aggregate basis would impose disproportionate and often insupportable requirements on operators, leading to an inconsistent regulatory environment." Although OneWeb's position regarding this question is not fully clear in its comment, it states in its reply comment:

[11] Amazon, Boeing, SpaceX, and Telesat.

"[r]eviewing collision risk on an aggregate basis would allow the full analysis of potential impacts of large NGSO constellations, which may include thousands of satellites" (OneWeb, Reply Comment, 2019, p. 4). Interestingly, NASA sticks to its practice and recommends the application of these metrics on a per-satellite basis.

Although the majority of respondents support the use of the metrics on a per-satellite basis, the FCC is licensing entire systems and thus must assess the impact a full system will have on the space environment. Applying the rule on the aggregate would, as correctly mentioned by SpaceX (2019, p. 15), result in "more lax regulations applying to satellites run by some operators than others." However, SpaceX's conclusion is misguided. When assessing if "the operations it authorizes are conducted safely and consistent with the public interest" (NPRM, 2018, p. 2), the FCC puts into the balance the service provided by an applicant and the impact it has on the space environment. As the benefits of the system are assessed in the aggregate, the costs[12] need also be computed in the aggregate. If the same service can be delivered with one or a hundred satellites, the metric must favor the use of the single satellite.

5.4.2.2 Orbit selection

The Commission proposes "that an applicant planning an NGSO constellation that will be deployed in the LEO region above 650 km altitude specify why it has chosen that particular orbit given the number of satellites planned, and describe any other relevant characteristics of the orbit such as the presence of existing debris" (NPRM, 2018, p. 13). The rules drafted by the FCC at the end of the NPRM do not limit this disclosure requirement to NGSO constellations but encompass all NGSO space stations.

The majority of respondents are against the inclusion of this disclosure requirement (4% for; 10% against; see Table 5.1). Iridium and SpaceX, which are the only respondents supporting this disclosure requirement, advocate for a more stringent rule. Iridium supports applying the rule to all applicants seeking to operate between 400 and 2,000 km, while SpaceX supports applying the rule to applicants planning to deploy a satellite at any altitude. Iridium (2019, p. 6) argues that such a rule would help "to ensure that unreasonable numbers of satellites are not launched to altitudes where they could interfere with the operations of the International Space Station and with other satellite operators."

[12] The increased collision risk in the space environment is a negative externality of a space system; thus, a cost.

An argument brought against this disclosure is its lack of usefulness for the FCC in assessing a license application: "It is still unclear based on the wording of the proposals how the FCC would determine an applicant has sufficiently justified their choice of orbit. What threshold of congestion would be considered too risky?" (Global NewSpace Operators, 2019, p. 8). OneWeb (2019, p. 21) also points out that the 650 km threshold is based on two flawed assumptions: "(i) that 25 years is an appropriate limit on post-mission orbital lifetime, and (ii) that 650 km is the appropriate altitude to correlate with a natural 25-year disposal."

The Commission asks whether it should "require all NGSO satellites planning to operate above a particular altitude to include propulsion capabilities reserved for station-keeping and to enable collision avoidance maneuvers, regardless of whether propulsion is necessary to de-orbit within 25 years" (NPRM, 2018, p. 14). Most respondents disagree with this proposition (8% for; 22% against; see Table 5.1), as they think that "the specific means of avoidance capability (i.e., propulsion capability) should not be mandated" (Telesat, 2019, p. 4). Only three companies—Iridium, LeoSat, and Maxar—would require propulsive capabilities as they believe that "[n]on-propulsive methods of maneuvering satellites remain largely experimental and it is unclear whether they are capable of effectively reducing collision risk" (Iridium, 2019, p. 6). Of the respondents against the proposition, ten out of eleven advocate for some maneuverability requirement above a threshold altitude (generally 400 km). They think that this requirement should be technology agnostic and that it should not preclude emerging technological alternatives. Some propose a performance-based requirement of maneuverability of the spacecraft, e.g., "requiring satellites to be capable of maneuvering at least 5 km within 48 hours of receiving a conjunction warning" (Amazon, 2019, p. 5) or requiring that operators can demonstrate that they can perform "collision avoidance maneuvers sufficient to reduce the probability of collision per conjunction for the spacecraft to less than 0.0001" (Telesat, 2019, p. 4).

The last point addressed by the Commission regarding orbit selection is whether it should "limit the variance in altitude above or below the operational orbit specified in an application for an NGSO system, in order to enable more systems to co-exist in LEO without overlap in orbital altitude" (NPRM, 2018, p. 14). The majority of respondents are against the adoption of a maximum limit for variance in orbit for NGSO systems (6% for; 10% against; see Table 5.1). The Commercial Smallsat Spectrum Management Association (2019) notes that such a rule would be difficult to sustain for propulsion-less satellites that drift downward over time and cannot maintain variance limits over their lifetime. Lockheed Martin and Orbcomm underline the difficulty in identifying meaningful bounds for the orbit variance at this stage. NASA (2019, p. 4) notes that "[t]he value is likely to be orbit-regime-dependent and evolve with improved technologies." For Telesat (2019,

p. 5), the problem with such rule is that it "might arbitrarily and unnecessarily bar use of valuable orbital real estate." Boeing (2019, p. iv) thinks exactly the opposite: "[i]n order to conserve scarce orbital resources, the Commission should adopt requirements that large NGSO systems adhere to their proposed orbits within certain identified limits." Interestingly, nor the Commission neither the respondents present any study that supports limiting the variance in altitude to mitigate the creation of space debris. This point is highlighted by Lockheed Martin (2019, p. 9), which states that there is "no present technical basis for adopting [such] a rule."

Some respondents do not directly address the question of maximum altitude variance but advocate for the licensing of a single constellation per altitude slot. To justify this, Iridium states that coordinating the movements of a constellation with those of another operator in an overlapping orbit is complicated. OneWeb (2019, p. 3) notes that "the merits of adequate inter-constellation spacing should be considered and codified." However, commentators are aware that the question of limiting altitude variance or licensing only one system per altitude is irrelevant without international cooperation (see § 3.1 regarding space appropriation and the definition of property rights in space). For example, one respondent notes that a Chinese operator projects to deploy 320 satellites at the same altitude as the OneWeb constellation (McKnight, 2018).

5.4.2.3 Design reliability

Following a suggestion by NASA in a comment filed regarding a proposed large NGSO satellite constellation, the Commission asks whether it would make sense to "impose a design and fabrication reliability requirement, for example, 0.999 per spacecraft, if a NGSO satellite constellation involves a large number of satellites or will be initially deployed at higher altitudes in LEO" (NPRM, 2018, p. 17). The FCC clarifies that it considers the deployment of 100 satellites over a typical 15-year license term to be a large number of satellites and that it considers higher altitudes to be those with a perigee above 600–650 km.

This proposition almost reaches a consensus against it in the comments (2% for; 26% against; see Table 5.1). OneWeb (2019, p. 9) finds this threshold "both unnecessarily and impractically stringent" but is not against introducing a 0.95 design reliability requirement. Other respondents highlight the additional cost that such reliability requirement would impose on them. The Global NewSpace Operators (2019, p. 12) are "not sure that requiring operators to prove some specific level of theoretical design reliability will always be sufficient to achieve the desired post mission disposal reliability targets by itself." More generally, commentators highlight that the focus should be on PMD reliability and not on satellite reliability. The Aerospace Corporation (2018, p. 13) notes that "[m]aximum flexibility should be permitted in how [the post-mission] disposal success rate is achieved" and that "a constellation-level design might include active retrieval as part of the mission concept or operational procedures to increase post-mission disposal reliability and ensure successful removal."

The rule is not well-targeted because the goal behind such a rule is to ensure the success of the PMD. It does not offer flexibility and constrain technological innovation on the spacecraft design reliability while other solutions might be more cost-effective. By enacting such a rule, the FCC would channel innovation in a specific direction, which is not the Commission's role. ADR or EOL services would thus be disadvantaged against improvement in satellite reliability, although both achieve the same end goal.

5.4.3 Post-mission disposal

5.4.3.1 Probability of success of disposal method

The FCC proposes that applicants "provide information concerning the expected reliability of disposal measures involving atmospheric re-entry, and the method by which that expected reliability was derived" and requiring a "probability of success of no less than a set figure, such as 0.90" (NPRM, 2018, p. 18). As for the collision probability metrics, the Commission asks whether it should apply the PMD reliability metric on a per-satellite basis or in the aggregate. It also asks whether large constellations should be held to a stricter standard.

The inclusion of a PMD disposal reliability metric in the FCC's rule is perceived positively by all but one respondents (16% for; 2% against; see Table 5.1), but most of them reject the idea of applying this metric on a system-wide basis (2% for; 10% against; see Table 5.1). The only respondent rejecting the inclusion of this metric is Lockheed Martin (2019, p. 13), based on the dubious arguments that "a casualty risk assessment is already required for reentry of objects" and that "[t]he Commission must avoid creating duplicative regulatory requirements and avoid adding burdensome requirements that do not advance the goal of reducing orbital debris in the long term." The first argument is unrelated, while the second is misinformed (see, e.g., Liou et al., 2018).

Most respondents would not compute the metric on the aggregate but require a different threshold to be met by large constellations. Boeing and OneWeb propose 0.95 for large constellations, which Boeing defines as having more than 100 satellites, and which are not defined by OneWeb. Telesat (2019, p. 8) thinks that "satellite operators should strive to satisfy a higher stretch target of 0.95 disposal reliability per satellite, [but that] mandatory compliance with this standard would be premature." NASA (2019, p. 6) is against using the metric on the aggregate as it "would give a skewed perspective of risk," but states that for constellation with more than 100 spacecraft the PMD reliability should be greater than 0.9, while for constellation with 1000 or more spacecraft the goal should be 0.99 or better (NASA cites its recent study to support these numbers; Liou et al., 2018).

As previously discussed in § 5.4.2.1, assessing the reliability in the aggregate makes the most sense for the Commission as it needs to balance the advantages of licensing a system (the service available to the public) and its disadvantages (the impact on the space environment). In this case, however, the metric does not fully encompass the impact a spacecraft that fails its PMD will have on the space environment as its cross-sectional area, mass, and altitude will matter.

In the case where the reliability threshold is different for large constellations, all respondents but the Global NewSpace Operators fail to recognize that defining the threshold for a large constellation in terms of the number of spacecraft is limited. Indeed, the Global NewSpace Operators propose the threshold to be more than 100 satellites or more than 10,000 kg of aggregate constellation mass. If a threshold were to be put in place for two different PMD reliability requirement, it should, as noted above, involve the cross-sectional area, the mass, and the altitude of the proposed system. However, this approach fails to recognize that the heightened risk of collision in the space environment due to failed PMD is a continuous function of these parameters. Including a single threshold would require very different standards for similar systems depending on whether they land above or below the threshold.

The FCC also proposes that applicants "certify that all satellites that will operate at an altitude of 650 km or above will be initially deployed into orbit at an altitude below 650 km and then, once it is determined that the satellite has full functionality, be maneuvered up to their planned operational altitude" (NPRM, 2018, p. 18–19). This requirement is not perceived positively by the respondents (2% for; 18% against; see Table 5.1). The most often raised concern regarding this requirement is the cost operators would have to bear due to the extra propellant needed and the curtailment of early revenue generation. Other seem to downplay the rationale for this rule: "[b]ecause spacecraft anomalies can occur at the beginning, middle and end of a satellite's operational life, an initial orbit below 650 km does not guarantee the satellite will not malfunction in a higher orbit" (Global NewSpace Operators, 2019, p. 13). However, studies agree that the satellite failure rates are higher in the first months following their launch (see, e.g., Castet & Saleh, 2009). Another concern raised is the meaning of the term "full functionality." For example, Sirius XM (2019, p. 6) wants the FCC to make sure "any functionality demonstration [apply] only to TT&C and maneuverability systems, not to payload systems."[13]

As already mentioned, arbitrarily setting a demarcation line at 650 km is based on two flawed assumptions, that the 25-years rule to de-orbit a spacecraft is the right benchmark and that this rule is perfectly correlated with orbits being below 650 km. If a demarcation line were to be imposed, this should depend on a satellite mass and cross-section, and be inline with an updated post-mission lifetime.

In its comment, NASA (2019, p. 7) notes that with this rule "the spacecraft would be required to transit through a highly populated altitude range." To properly assess the effectiveness of this requirement, studies would have to be performed to assess the collision risk while raising the orbit of numerous spacecraft through altitudes with a high density of debris.

An often proposed solution to the inability to perform PMD maneuvers successfully is to require the automatic disposal by a de-orbiting device. The FCC addresses this question by proposing that applicants "provide a statement that spacecraft disposal will be automatically initiated in the event of loss of power or contact with the spacecraft, or describe other means to ensure that reliability of disposal will be achieved" and asks "whether [it] should simply require the design to include automatic disposal by a de-orbiting device in the event of loss of power" (NPRM, 2018, p. 19). Respondents are mostly against this idea (6% for; 16% against; see Table 5.1). The Global NewSpace Operators (2019, p. 13) underline that "many constellations will be using low-thrust propulsion systems that can require multiple months of continuous operations and control in order to move from an operational orbit to a safe orbit" and thus "an automatic initiated disposal is not practical in this case." Another point of concern is what would be the trigger for the automatic de-orbiting. Orbcomm (2019, p. 18) notes that "accounts of satellite operators recovering spacecraft following failures are not at all uncommon" and that "[s]etting a trigger for automatic de-orbiting too soon after a failure could result in taking spacecraft out of service that could very well have been restored." The confidence in the ability of an automatic de-orbiting mechanism or device to perform successful PMD maneuvers is low, as can be seen from Telesat's comment (2019, p. 8): "autonomous deorbit risks increasing collisions and orbital debris due to unpredictable thruster operation."

[13] TT&C stands for telemetry, tracking, and control.

5.4.3.2 Post-mission lifetime

Following the ongoing debate in the space community regarding post-mission lifetime, the Commission asks "whether the 25-year disposal guideline contained in the NASA standard remains a relevant benchmark" (NPRM, 2018, p. 22). This question is the most addressed of the 15 selected for this analysis showing the broad interest in this matter. The majority of respondents favor shortening the disposal guideline (28% for; 8% against; see Table 5.1), but do not agree by how much.

According to SpaceX and Iridium, operators should remove their spacecraft from orbits as soon as they reach the end of their operational life and be required to do so in a maximum of five years following the spacecraft's end-of-life (EOL). Iridium (2019, p. 8) argues that "[r]equiring deorbit should not impose a tremendous burden on operators as the additional cost to deorbit within 5 years rather than 25 is relatively minor." The Global NewSpace Operators (2019, p. 16) also support this 5-year limit after EOL but would allow "a passive deorbit approach (i.e. drag sail) utilizing up to the full 25 year deorbit window [...] in some cases [such as] university cubesats, science focused payloads or one-time demonstration missions." OneWeb and Intelsat propose to limit the post-mission lifetime to two times the operational lifetime of the satellite. Moreover, OneWeb proposes to cap the post-mission lifetime to a maximum of five years. Tying the post-mission lifetime to the mission lifetime brings some concerns to Boeing (2019, p. 17), which argues that "this proposal may have the unintended consequence of prompting satellite operators to develop mission plans that are more lengthy than necessary." Some respondents argue that a hard boundary should not be the way forward, but that the post-mission lifetime should be risk-based and take into account the orbital altitude, the cross-section, and the operating lifetime.

Other respondents think it is not time to revisit the post-mission lifetime rule. Orbcomm (2019, p. 12) thinks it is "premature to select a specific shorter time period," while Telesat (2019, p. 8) thinks that "there is no apparent reason to change the guideline, but it may be in the public interest to do so in the future." NASA (2019, p. 7) argues that its recent constellation study has shown that this rule remains "a sufficient benchmark for limiting the growth in the debris environment." However, to the best of my knowledge, Liou et al. (2018) do not address this question, and no other NASA study on this matter is publicly available. Furthermore, Lucken and Giolito (2019, see their Figure 6) have shown that shortening the post-mission lifetime does reduce the impact on the space environment.

5.4.4 Liability issues and economic incentives

The Commission acknowledges that the United States government, as a signatory of the Liability Convention (see § 4.1.1.2), "could potentially be presented with a claim for damage resulting from private satellite operations such as disposal or generation of orbital debris" and notes "that the Commission is a regulatory agency, and unlike agencies with statutory authority to conduct space operations, cannot accept risk on behalf of the United States by virtue of undertaking those operations" (NPRM, 2018, p. 27). The FCC thus asks "whether Commission space station licensees should indemnify the United States against any costs associated with a claim brought against the United States related to the authorized facilities" (NPRM, 2018, p. 27). All but one respondent support this proposition (2% for; 24% against; see Table 5.1). LeoSat (2019, p. 9), which is now out of business, is the only respondent that "supports the Commission's objective to require Commission-authorized operators to enter into indemnification agreements." As this requirement would impact both GSO and NGSO operators, the share of GSO satellite manufacturers and operators commenting on this question is greater than in the other questions analyzed. Some commentators[14] question the authority of the Commission to regulate the indemnification of the US government, while other are worried that such a requirement might affect the competitiveness of the US space industry, stifle innovation, or drive licensing abroad. For example, Space Logistics (2019, p. 3) believes that "Congress, not the FCC, should balance the trade-offs between protecting the United States government from liability and encouraging the growth of the domestic commercial space industry," and Intelsat (2019, p. 12) states that the "NPRM does not identify a legal basis for FCC authority to impose an indemnification requirement." AT&T (2019) even proposes that if the Commission decides to adopt this proposal, the indemnification requirement should only apply to NGSO licensee and not GSO licensee, without providing a convincing argument for this distinction.

Another area of concern is the availability of insurance at reasonable rates to cover the risk of indemnification. Orbcomm (2019, p. 19) notes that "without insurance to fund an indemnification liability, it is very likely that defaults on such obligations could easily occur, rendering such a requirement ineffective and unenforceable." As the requirement in the NPRM does not place a cap on the indemnification, securing unlimited third-party insurance for a potentially unlimited amount of time does not seem achievable.

[14] Space Logistics, Intelsat, EchoStar, and Lockheed Martin.

5.4.5 Scope of rules

As a final matter, the Commission addresses the question of to whom the rules should be applied. The Commission is aware that a "categorical exemption for any class of satellites serving the United States would undermine the legitimate public policy objective of mitigating orbital debris" (NPRM, 2018, p. 30). The FCC thus proposes that the rules should also "be applicable to non-U.S.-licensed satellites seeking access to the U.S. market," which means that "an entity seeking access to the U.S. market must continue to submit the same technical information concerning the satellite involved as is required to be submitted by U.S. satellite license applicants" (NPRM, 2018, p. 30). Finally, the FCC proposes "that non-U.S.-licensed satellites may continue to satisfy the disclosure requirement by showing that the satellite system's debris mitigation plans are subject to direct and effective regulatory oversight by the satellite system's national licensing authority" (NPRM, 2018, p. 31). The FCC thus asks if the assessment of the effectiveness of the foreign regulatory authority should continue to be performed on a case-by-case basis.

Respondents agree that the rules presented in the NPRM should also be applied to non-US-licensed satellites seeking access to the US market (18% for; 0% against; see Table 5.1). They also agree that an operator would satisfy the disclosure requirements by demonstrating that its satellites are subject to direct and effective oversight by a foreign regulatory authority. The commentators agree that exempting non-US-licensed satellites from these rules would encourage forum shopping. For example, EchoStar (2019, p. 8) states that "[e]xempting non-U.S.-licensed satellites from orbital debris mitigation regulations undermines the effectiveness of their implementation, and encourages satellite operators to seek authorization from the least onerous administration prior to petitioning for market access in the United States." The commentators do not challenge the practice of assessing the foreign regulatory authority regarding space debris mitigation on a case-by-case basis. If the FCC enacts the rules proposed in the Notice, it will have more stringent rule than most foreign regulatory authorities. Thus the question of whether the Commission would assess those authorities as performing an *effective* oversight remains open. If the threshold of effectiveness is the new rules enacted by the FCC, foreign regulatory oversight would not be sufficient, as their rules are less stringent. Thus non-US-licensed satellites seeking market access in the US would have to abide by the FCC rules.

5.4.6 Discussion

5.4.6.1 The FCC's ability to make space more sustainable

As we have seen, the FCC has a broad reach: a large share of the future launches will be communication satellites, operators of the largest constellations planned are American, and the US is a large market which most operators want to access. By its authority to grant market access to non-US-licensed operators, the FCC can make space more sustainable by requiring the non-US-licensed operators to abide by the same rules. If the FCC were to enact more stringent rules than its foreign counterparts, it remains to be seen if a case-by-case assessment of the foreign regulatory oversight will result in the conclusion that the counterpart rules are not sufficient and the FCC directly applying its rules to the non-US-licensee.

Respondents to the Notice have emphasized the need for a more homogeneous and unified space debris policy framework. While such an endeavor might be attainable in the US, reaching an international agreement on this matter seems out of reach (e.g., Kurt, 2015). In the US, the ongoing interagency process and the willingness to develop SSA and STM capabilities might result in the creation of a new entity—or the centralization in an existing one—responsible for all space matters. Such a process is necessary to unify the requirements regarding space debris mitigation across commercial space activities. Indeed, remote sensing activities will be a non-negligible share of future launches, and the same rules should be applied to those activities. If the US were to put a unified framework for space debris mitigation in place, with more stringent rules than currently applied elsewhere, we could imagine other countries (e.g., EU countries, Australia) following the impetus.

The FCC reform of its orbital debris rules does not fit well in the Trump administration's space policy strategy. The administration wants to streamline the licensing procedures and remove the potential barriers to the development of the commercial space economy. However, enacting more stringent orbital debris rules adds some administrative burden and constrain operators' activities.

5.4.6.2 Feasible, efficient, and effective rules

There is common agreement between the respondents that the rules enacted should be performance-based, do not prescribe the use of a technology, and should provide the Commission with a clear way of assessing an applicant's license request. Three aspects of orbital debris mitigation are key in ensuring a sustainable space: reducing the likelihood of catastrophic collisions, the probability of PMD failures, and the time objects stay in orbit after their EOL.

To address the first aspect, the Commission proposes the inclusion of a collision probability metric and some disclosure requirements, such as why an orbit has been chosen and the presence of existing debris at the planned orbit. It is unclear how the Commission will treat the disclosure requirements, and thus those rules do not offer regulatory certainty and predictability. Requiring that a spacecraft's collision probability with large objects over its lifetime be smaller than a threshold is feasible, effective, and efficient. Although modeling assumptions impact the computation of this metric, we can derive a meaningful number for this probability. Mandating the use of a specific tool or methodology to derive this metric could mitigate the concern that the model is adjusted by operators to fit their needs, and provide for equal treatment of the applicants. This rule is both efficient and effective, as it directly targets reducing the risk of collisions and does not mandate any technology or constrain specific operations. The threshold has to be informed by scientific evidence,[15] and could be revised in the future. As discussed in § 5.4.2.1, the metric should be computed in the aggregate as the licensing of a system must balance its overall benefits for the public with its overall impact on the space environment.

A vast number of studies have shown that PMD reliability and duration are the key parameters that will affect the orbital debris population growth (e.g., Liou et al., 2018; Radtke et al., 2017; Somma et al., 2018). The Commission proposes various rules to maximize the PMD reliability, including a metric on small object collision risk, a metric on design reliability, the initial deployment below a threshold altitude, and a metric on PMD reliability. Some of those rules do not directly address the end goal and are thus inefficient in tackling the problem. For example, requesting some threshold of satellite design reliability might preclude the development of more cost-effective solutions (e.g., ADR).

A single performance-based rule could meet the end goal without prescribing the solutions: a PMD reliability metric with a threshold dependent on the mass, the cross-section, and the debris density at the planned altitude of the system. A satellite which does not manage to perform its PMD successfully will have a different impact on the space environment depending on its mass,[16] its cross-section,[17] and the debris density[18] at its altitude. The overarching goal is that the rate of debris generation does not preclude the future use of near-Earth orbits. This translates into a different threshold of the PMD reliability at different combinations of these three parameters. At certain combinations, the PMD reliability could even be 1 (i.e., all satellites be de-orbited). A PMD reliability requirement of 1 would likely

[15] The threshold should preclude the growth of the debris population given the planned launches and current debris environment.

[16] The bigger, the more debris created in a collision.

[17] The bigger, the higher the collision probability.

[18] The higher, the higher the collision risk.

result in the absence of launch until a retrieval service is available. To which extent each variable impacts the PMD reliability requirement should be explored through modeling.

Setting the PMD reliability thresholds is a daunting task as our knowledge of the rate of debris generation that does not preclude the future use of near-Earth orbits is limited. The same difficulty arises when setting the post-mission lifetime (see discussion in § 5.4.3). Regulatory authorities, operators, and academia are cognizant that we face a high degree of uncertainty in assessing the space environment status, and the effects policy measures have on it. While funding research on the topic is a necessary step to reduce this uncertainty, the timescale on which the Kessler syndrome might be happening limits the uncertainty reduction possible. Two approaches are thus available to address the space debris problem from a regulatory perspective: wait-and-see and precautionary. Under the wait-and-see approach, we wait until further information is available to take action. This approach has been followed, for example, by the interagency group lead by NASA, which decided to keep the 25-years post-mission lifetime rule unchanged in the ODMSP. Short-run economic interests often guide this strategy. The precautionary principle is the opposite strategy to deal with the uncertainty in the assessment and management of risks (World Commission on the Ethics of Scientific Knowledge and Technology, 2005). It calls for action to prevent potentially irreversible damage to the environment (here the Kessler syndrome) before a clear causal link between the damage and the measure has been established by scientific evidence. The Rio Declaration on Environment and Development (1992, Principle 15) states: "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." Here, the full scientific evidence is not lacking, but the strength of the measures that need to be taken to prevent irreversible damage is uncertain.

Finally, a core aspect of a policy is its enforcement mechanisms. The FCC has detailed only ex-ante requirements without specifying the means for their enforcement. What would happen if operators do not respect the statements made in their application? Would the Commission have the tools to enforce its rules? Would the Commission have the ability to take into account an applicant's behavior in its future applications? Market-based approaches which are explored in chapter 6 alleviate the enforcement problem. For example, regarding the PMD reliability metric for large systems, one could imagine applying the rule ex-post with a fee for non-compliance (see § 6.2).

5.5 New rules and further propositions

On April 23, 2020, the Commission released a Report and Order and Further Notice of Proposed Rulemaking (R&O and FNPRM, 2020) regarding the "Mitigation of Orbital Debris in the New Space Age." Due to the pressure from the government and industry (e.g., Henry, 2020b), the FCC decided to postpone the adoption of the most controversial rules.[19] The FCC concluded that it has authority to review orbital debris mitigation plans but acknowledged the need for coordination with other federal agencies. Contrary to demand from the industry and government, the FCC argues: "Given the pace that the industry is evolving, and our responsibility to continue licensing satellites and systems on a day-to-day basis, we find that it would not be beneficial at this time to delay our rule updates" (R&O and FNPRM, 2020, p. 12).

The last columns of Table 5.1 presents the FCC's decision regarding the 15 items discussed in § 5.4. All rules which had a majority of commentators supporting them—except the reduction of the 25-years rule—have been adopted by the FCC. More stringent rules for multi-satellite systems, such as the computation of probability thresholds on an aggregate basis, have been moved to the FNPRM. In areas which the ODMSP address, the FCC has not enacted more stringent rules. The relatively weak standards adopted in the recent revision of the ODMSP (see § 5.2) seem to have hindered the FCC revision of its orbital debris rules. Indeed, it is hard to require a much higher standard for commercial activities than for missions operated or procured by US government agencies.

In the FNPRM, the Commission broadens the discussion and request further comments on debated items of the NPRM. The FCC especially asks comment on the use of a more stringent threshold or the computation on an aggregate basis of the probability of collisions with large objects for multi-satellite systems, a maneuverability requirement above a certain altitude in LEO, the reduction of the 25-years rule, and the indemnification requirement. The FCC also seeks comment on two new rules: the inclusion of the ODMSP threshold on the probability of accidental explosion and a performance bond for successful disposal. For the latter, the FCC seeks comment on "adopting a requirement that space station licensees post a surety bond [...] that would be returned once the space stations

[19] Following two letters sent to the FCC by the Aerospace Industries Association (AIA Comment, 2020) and the Satellite Industry Association (SIA Ex Parte Presentation, 2020) criticizing the proposed rules, the House Committee on Science, Space, and Technology asked the commission to "delay consideration of this matter" arguing that "[s]takeholders have communicated significant concerns with the proposed rule," which contradicts with "Executive Branch policy and is inconsistent with existing and proposed legislative action" (House Committee Letter, 2020).

authorized have successfully completed post-mission disposal" (R&O and FNPRM, 2020, p. 90). This proposal follows from the difficulty in ensuring that licensees respect their planned orbital debris mitigation plan. Such a proposal deviates from the command-and-control approach adopted by the FCC. It would create a strong incentive for operators to take space debris generation into account in their decisions, as it would directly affect their bottom line. I detail this FCC proposal as part of the discussion on regulatory fees in § 6.2.2.

6 Market-based approaches to the orbital debris problem

In chapter 5, I discussed the ongoing space policy reforms in the US addressing the space debris problem. The new rules proposed by the FCC focus on a command-and-control approach with ex-ante requirements. I discussed the content of the requirements, their relevance, and perception by stakeholders. In this chapter, I detail more broadly the policy alternatives available to the regulator.

In a command-and-control approach, the regulatory authority prescribes what is allowed or not. This approach includes, e.g., technical specifications, limits on inputs or outputs, or requirements to disclose information. An alternative regulating approach is to use economic incentives.[1] By deploying economic instruments, such as subsidies or taxes, the regulator can encourage or discourage behaviors. Those market-based instruments are often claimed to provide numerous advantages, including a lower level of regulatory discretion, being cheaper to administer, and providing managers with flexibility in their decision-making. Overall, market-based mechanisms are often seen as a cost-effective way of addressing market inefficiencies (however, see discussion of their drawbacks in Baldwin et al., 2012, chapter 7). Different regulatory strategies have a varying ability to generate "externality-reducing innovation." Benefits of resource improvements are not internalized under a command-and-control approach, and thus resource-renewing or resource-preserving investments are not incentivized (J. B. Taylor, 2011). Market-based mechanisms internalize the benefits of such investments and thus encourage them. Another advantage of market-based mechanisms is that they often generate money that can be channeled at the policy objective and provide further benefits.

The idea of using market-based alternatives to internalize the global externalities of orbital debris is not new. As early as 1986, Scheraga discussed the possibility of using Pigouvian taxes in the space debris context. More recently, in its reply

[1] See, e.g., Baldwin et al., 2012, chapter 7, for an overview of regulatory strategies, and Wiener, 1999, for their application at the global level in the environmental context.

comment to the FCC's NPRM on new rules for orbital debris mitigation, the Institute for Policy Integrity (2019) detailed various market-based approaches to the orbital debris problem and urged the Commission to consider them. I draw extensively on this reply comment in this chapter.

In the following sections, I examine the different market-based approaches available to curb the proliferation of orbital debris. For each approach, I first detail its general features and assess its applicability in the space debris context. I analyze how the key features should be designed to maximize the approach efficiency and effectiveness. A review of the proposals made in the literature is conducted to inform this analysis. In § 6.1, I look at two flavors of marketable permits: cap-and-trade and credit trading. I then look at regulatory fees or Pigouvian taxes in § 6.2. Those two schemes similarly internalize the space debris externality and rely on a program directly administered by the regulatory authority. An alternative is to rely on the insurance market to provide the necessary incentives to reduce space debris; this option is assessed in § 6.3. The relatively week liability standard provided by the international legal framework governing space could be supplemented by the doctrine of market-share liability. I evaluate this approach and its extension to a retrieval fund to provide market-share disposal payments in § 6.4.

6.1 Marketable permits

Marketable permits (see, e.g., OECD, 1998, Schwartz, 2017, for an overview) are "government-created licenses or obligations for a specific level of a particular activity" (Schwartz, 2017, p. i). In other words, a marketable permit is a right or duty to take a defined action. Those permits can be "bought or sold independently of any real property or interest" and can be "traded on primary markets, secondary markets, or both" (Schwartz, 2017, p. i–2). The primary market is the first allocation of the permit by the regulatory authority, while the secondary market encompasses all subsequent exchanges. The initial distribution can be executed through a market mechanism (e.g., an auction), a lottery, or on a criteria-based rule. The exchanges on the secondary market can be forbidden or limited.

Marketable permits have been most prominently used in environmental and energy policies for natural-resource and pollution management. Marketable permits have typically been established to ration the use of CPRs (e.g., control air pollution and GHG emissions, manage water supply and fisheries; Tietenberg, 2006), but have also been used to favor the production of under-supplied goods or actions (e.g., tradable obligation to produce a given amount of renewable energy; Engel, 1999). They have also been applied in other domains such as transportation (e.g., to allocate taxi medallions) or communication policy (e.g., to allocate the electromagnetic spectrum).

Two broad categories of marketable permits exist: cap-and-trade and credit trading (also known as baseline-and-credit, or rate-based trading). In a cap-and-trade system, the regulator sets an *absolute* budget—the cap—for the activity regulated (e.g., the total amount of fish catches allowed), while in a credit trading system, the regulator sets the *relative* amount of an activity (e.g., no net emission increase) that can take place.

In many contexts, empirical evidence shows that, compared to traditional regulation, marketable permits lower compliance costs, incentivize innovation (weak evidence), and can reduce the administrative burden (Harrington & Morgenstern, 2006; Tietenberg, 2006). These advantages depend on the context and the method of application (see discussion in Schwartz, 2017). Compared to prescriptive regulation, marketable permits "rely on the market to identify the most cost-efficient way to allocate regulatory privileges or obligations" (Schwartz, 2017, p. i). In Table 6.1, I compare the application of a command-and-control to a cap-and-trade approach for two typical examples of policies where both approaches have been applied: reduction of pollutants and allocation of the electromagnetic spectrum.

There are two requirements to apply marketable permits to a CPR problem, such as orbital debris. First, the compliance cost (e.g., the abatement cost in case of emission or debris creation reduction) across the entities regulated should differ. If these costs are the same, then the marketable permit scheme has no efficiency gains compared to the command-and-control approach. Moreover, these abatement cost differentials are necessary to drive the supply and demand of marketable permits. Second, the activity to be regulated must be fungible.[2] When, where, and by whom the regulated activity is conducted should not matter to the regulator. The trade of the marketable permits among actors should not hamper the policy goal. The prime example of a fungible activity is GHG emissions. However, complete fungibility rarely exists for other kinds of regulated activities (Tietenberg, 2006). That is why, the unit of exchange of the activity regulated—the "currency"—must be carefully designed to maximize fungibility and avoid that the externalities escape the trading market (Salzman & Ruhl, 2000). As the goal to be achieved (e.g., social welfare) is usually hard to measure, the currency is, most of the time, a proxy measure.

[2]A good or commodity is said to be fungible if its individual units are interchangeable, and each of its parts is indistinguishable from another part.

Table 6.1 – Comparison between a command-and-control approach and a cap-and-trade mechanism for two typical examples of policies where both strategies have been applied.

Policy goal	Command-and-control	Cap-and-trade	Cap-and-trade advantage
Reduce emission of a pollutant	Require every single polluter to comply with an emission standard or/and mandate the use of a specific technology.	Set the maximum budget of emissions and leave individual polluters to decide for themselves if they want to emit more and buy permits or to emit less and sell permits.	Emissions are reduced where it costs the less: individual polluters with the lowest abatement costs reduce their emissions.
Allocate electro-magnetic spectrum	Set an administrative process to collect information on the applicants and assess the value of the spectrum to applicants. Once assigned, the spectrum is difficult to reassign.	Auction spectrum licenses, which can then be re-sold.	The regulator does not need to guess which applicant gets the most value from the spectrum, but a market mechanism ensures it.

6.1.1 Marketable permits in the space debris context

Are marketable permits appropriate in the orbital debris context? Two aspects must be primarily addressed: abatement cost differentials and fungibility of the externality. Costs to reduce the amount of debris released during normal operations or for avoiding the loss of a spacecraft differ across space operators. The costs to mitigate or remediate space debris are also expected to evolve with technological innovations. The latter are unlikely to be equally shared among actors and will yield further compliance cost differentials. Because of these differences in abatement costs, marketable permits are more efficient than command-and-control regulations.

The characterization of the negative externality produced by space activity is crucial for its fungibility. Space debris is a byproduct of space activity and thus is often thought of as the externality. However, space debris is not fungible as pieces of debris have diverse masses, cross-sections, and orbits. By comparison, a unit of debris-related risk is fungible. It can be traded without the externality getting out of the trading market. This statement holds only for a given definition of risk, which is informed by the policy goals.[3] If we assume that some orbits are more valuable than others and should be preserved more, then the risk definition must encompass this aspect. For example, solely taking the collision probability as the unit to be traded would allow trading a unit of collision probability in a valuable orbit to one in an invaluable one, leading to a leak of the externality. This highlights that the unit of risk to be traded, i.e., the currency, must be carefully designed to fit the policy goal.

6.1.2 Features of a marketable permit approach for space debris

6.1.2.1 Designing the currency

In a marketable permit scheme, the currency must fulfill three requirements: it must be aligned with the policy objective, be fungible (to the largest extent possible), and the regulatory authority must be able to quantify and monitor it.

We can broadly define two policy objectives: (i) protect the operational assets from collisions, and (ii) protect the space environment from a potential Kessler syndrome that might render some orbits unusable. The second goal takes a long-term perspective on space debris, and could as a byproduct result in the fulfillment of the first goal. As we have seen in § 3.3.2, valuing different orbits is a difficult task, especially as there is high uncertainty in their future value. By pursuing the second goal, we would assume that all orbits are equally valuable, whereas by pursuing the first one, only orbits where operational assets are located would be valued. To address those two policy goals, an appropriate definition of risk is needed. For this purpose, we segment near-Earth orbital space in altitude shells of appropriate size (e.g., 50 km). For (i), we can then define for a time period t (e.g.,

[3] Risk is often defined as the probability of an event occurring times its economic consequences (or damages). The scope of economic impacts considered is thus of high relevance (see § 3.3.2). If only damage to operational assets is considered, the resulting debris-related risk will be different than if all potential collisions are considered.

a year), the risk in an altitude shell S as

$$r_{S,O,t} = \sum_{i \in S \cap O} p_{i,t} \times v_i, \tag{6.1}$$

which is the sum over all operational assets O in altitude shell S of the product of an asset's collision probability p over the time period t with its value v. The probability p can be calculated using a model of the debris environment (e.g., MASTER or ORDEM), but the value v is more challenging to estimate. The book value of the assets could be accessed but is a weak proxy of the value society reap from those space assets. Revenue is a better proxy but can only be applied to commercial assets.

Similarly, for (ii), the risk for a time period t in an altitude shell S would be

$$r_{S,T,t} = \sum_{i \in S \cap T} p_{i,t} \times m_i, \tag{6.2}$$

which is the sum over all trackable objects (operational assets and debris) T in altitude shell S of the product of an object's collision probability p over the time period t with its mass m. The mass of an object is a good proxy of the number of objects generated by a collision (see NASA breakup model for collisions; N. Johnson et al., 2001) and thus of the potential damage on the space environment.[4] Some of the non-trackable objects could generate a catastrophic collision and should theoretically be included in the risk measure. However, as they are not tracked, it is not possible to estimate their collision probability. In what follows, we design a currency aligned with the second policy objective for two main reasons: the mass of space objects is a far more accessible information than their value, and preserving the long-term use of space is a better objective than only focusing on operational assets.

The overall increase in collision probability due to a newly created piece of debris depends on three parameters: the piece of debris' lifetime,[5] the density of objects at its altitude,[6] and its cross-section.[7] However, the impact or damage to the space environment depends heavily on the mass of the newly created piece of debris. To enable a comprehensive reduction of risk, these four parameters should be taken into account in the design of the currency. By taking them into account, it

[4] The number of objects is the key parameter that determines the number of collision avoidance maneuvers operators must perform and thus determines if an orbit is economically usable.

[5] The longer the debris is in orbit, the higher the risk of collision. The lifetime of a piece of debris depends on its altitude, mass, cross-section, and the solar cycle.

[6] Some altitude are more crowded than other, and thus result in a higher risk of collision.

[7] The larger the cross-section, the higher the risk of collision.

makes the currency fungible. If we were to take, e.g., only the number of debris generated as currency, we would neglect the fact that different pieces of debris have a fundamentally different impact on the environment depending on the above-mentioned factors. Taking different dimensions (which are on different scales) into account in the currency requires aggregating them. This process involves weighing the impact of the dimensions on the space environment, which is subject to limited empirical evidence and could be open to endless negotiations. One way to solve such a conundrum is to model the risk increase for any new debris. For each new trackable debris, the resulting incremental risk in its altitude shell S over the time period t is

$$\Delta r_{S,T,t} = \sum_{i \in (S \cap T)_{\text{With new debris}}} p_{i,t} \times m_i - \sum_{i \in (S \cap T)_{\text{Whitout new debris}}} p_{i,t} \times m_i, \tag{6.3}$$

where $(S \cap T)_{\text{Without new debris}}$ is the ensemble of trackable objects in the shell before the generation of the new debris and $(S \cap T)_{\text{With new debris}}$ is the ensemble of trackable objects in the shell after it. Although modeling has limitations, it gives a reliable and comparable estimate of the risk increase resulting from new debris. An important question regarding this calculation is which time period t should be considered. To fully account for the incremental risk posed by a new piece of debris, this calculation should be performed on the piece of debris' lifetime. However, the longer the time period, the higher the uncertainty on the collision probability calculation, as the intensity of the future solar cycles and the launch traffic are difficult to predict. To avoid making these predictions, the incremental risk could be computed periodically. For example, the incremental risk created by the piece of debris would be computed each year for a one-year period. This method reveals a new question. Should the future launch traffic be taken into account? Let us take the example of a new piece of debris at a currently unused altitude, which becomes intensely used ten years from now. If computed periodically, the incremental risk would suddenly spike when the orbit becomes used more frequently. Should the actor responsible for the piece of debris be paying for a future risk which it cannot foresee? Comprehensively pricing the externality would require taking into account the future launch traffic, as this newly created piece of debris will generate a cost on the future users of the orbit. Moreover, this would somehow solve the difficulty in estimating the future value of orbits, as the ones becoming used more intensely must have a substantial value. However, one obvious problem with this method is the lack of certainty for operators. It could also be argued that this method is unfair. One option would be to calculate the risk increase in a short time period (e.g., a year), thus avoiding assumptions on future launch traffic and exogenously adjusting the risk increase by the predicted debris lifetime. This would still rely on assumptions regarding the solar cycle.

Salzman and Ruhl (2000) argue that while theoretically attractive, comprehensive currencies designed to account for non-fungibility across type, space, and time impose a heavy informational burden on the entities responsible for designing and supervising the trade program. This increased complexity results in increased transaction costs and reduces the potential efficiency of the program. As the use of a modeled $\Delta r_{S,T,t}$ for each newly created piece of debris might not be practical or too complex, a simpler formula based on a set of representative simulations might be derived and offer a sufficiently reliable proxy.

The regulatory authority must be able to monitor the different parameters that enter the currency and verify the operators' disclosures. As it would be impossible to determine the values of those parameters (e.g., the number of debris released, their altitude, etc.) before launch, those should be evaluated post-launch, on an ongoing basis. Periodically (e.g., once a year), the regulatory authority should verify that operators have the correct number of permits corresponding to the number of units of risk they have created during the period. If the risk creation over the piece of debris' lifetime is computed at a single point in time, the permit must cover this overall risk. If the risk is assessed over a defined period, the operator should have permits covering the risk for that period. With the latter option, if the operator goes bankrupt, it will no longer purchase the permits in a commensurate amount with the debris-related risk. Moreover, this accounting method might provide a smaller incentive for operators to purchase a retrieval service, as permits requirements are diluted over a longer period of time.[8] Liability rules for non-compliance must be enacted to ensure compliance and that the program achieves its policy objectives.

In the risk definition in Equation 6.2, all the orbits are treated equally. If we value some orbits more, and thus a stronger focus on their protection is warranted, trading ratios can be used. Such ratios account for the imperfect fungibility of the unit of risk defined with respect to the policy objective (Schwartz, 2017). For example, if the policy objective is not only (ii) but also encompass (i), then the definition of risk in Equation 6.2 is not perfectly fungible. Looking at the value insured in LEO and GEO (see Figure 6.2), we can assume that there are more valuable assets in GEO than in LEO. Thus, the regulator might value risk differently in these two orbital regimes. To account for that, the risk definition in Equation 6.2 could be modified or trading ratios used. Let us assume that the regulator values twice as much risk reduction in GEO than in LEO. Then imposing that two units of risk in GEO can be traded for one unit of risk in LEO accounts for this preference. This mechanism could be extended to multiple altitude shells.

Trading ratios are not only useful to correct imperfect fungibility but can be used

[8] If operators heavily discount the future expenses for permits, this will reduce their incentive to retrieve debris.

for two other purposes (Institute for Policy Integrity, 2019; Schwartz, 2017). First, they can be used to mitigate uncertainty and ensure risk reduction when it is impossible to monitor or predict the risk creation precisely. This prevents actors from reducing less than expected their quantity of debris created. If an actor plans to reduce the quantity of risk it creates in a given period by x units, and if the trading ratio is t (with $t < 1$), then the actor can only sell permits for $x \times t$ units of risk. In the case where the actor reduced its risk creation by less than x units, this is offset (at least partially) by the trading ratio. Second, trading ratios can be used to further the policy goal. They could be used to incentivize the development and use of retrieval technologies. Due to economies of scale and learning effects, a sufficient number of retrievals need to be performed to reach a competitive cost. Thus, it might be interesting for the regulator to specially promote the use of such technologies, at least in a first phase. An actor reducing the space debris-related risk by x units through the use of a retrieval technology would be able to sell permits for $x \times t$ units of risk (here with $t > 1$).

6.1.2.2 Cap-and-trade versus credit trading

Under a cap-and-trade program, the regulator would first set an overall maximum budget of permitted amount of debris-related risk creation per time period. Calculating the optimal level of debris-related risk creation is a difficult task and requires access to sufficient information (Tietenberg, 2006). A cost-benefit analysis of orbital debris generation should provide the necessary tool to set the cap maximizing net benefits. However, the necessary information might not be available (see § 3.3.2 and § 3.3.3), and debate regarding the boundaries of the analysis might occur. For example, in its comment to the FCC's NPRM on orbital debris rules, the Institute for Policy Integrity (2019) urged the Commission to weigh direct and indirect costs and benefits globally. The scale of the cap-and-trade program, i.e., the number of jurisdictions involved, would affect the cap. To achieve the policy objectives and to create enough demand for permits to support the market, the cap must be sufficiently stringent (Schwartz, 2017).

Once the cap is set, the regulator must define a mechanism to allocate the permits. The amount of debris-related risk creation per time period should be allocated at the start of each time period. This allocation can be an auction, a lottery, or based on some criteria. Under certain circumstances, the market equilibrium is not affected by the initial allocation, and the cap-and-trade system is cost-effective (Hahn & Stavins, 2011). However, auctioning permits combined with revenue-recycling can improve efficiency (Goulder & Parry, 2008; Goulder et al., 1999). At the same time, it would generate funds that the regulator can channel into research and development of mitigation and remediation measures, as well as SSA and STM. In a second phase, once retrieval methods have matured, the regulator could use the money collected to engage directly in ADR. In the case of emission allowances, auctions have been opposed by some industrial sectors arguing that pricing the externality without compensation would harm international competitiveness (Zetterberg et al., 2012). Such an outcome could arise in the case of space debris if the cap-and-trade program is not applied globally. When stakeholders can influence the policy choice, free distribution of permits can increase the feasibility of implementing a cap-and-trade system (Raymond, 2003).

An alternative market structure is a credit trading system. Its main advantage is that it does not require the regulatory authority to set a cap, which is potentially difficult given the information available. Instead, the regulator sets a relative baseline on the amount of debris-related risk creation, i.e., it sets a baseline level of debris-related risk creation per unit of some input or output by the regulated firms (Boom & Dijkstra, 2009). Actors generating more risk than the baseline allows must purchase permits to compensate the difference while actors creating less risk than their baseline can sell permits for the difference. In the space context, debris is generated by different actors—operators and launchers—which have different inputs and outputs and do not provide the same benefits. Finding the appropriate performance-based baseline is difficult, as it should be tied to the benefits produced by space activities, which are almost impossible to measure. Furthermore, a simple proxy measure for those benefits is not available. One could imagine capping the number of debris-related risk units created by launchers and operators separately. For launchers, the baseline number of debris-related risk units could be tied to the number of launches or the operational mass put into orbit. For operators, the permitted rate of debris-related risk creation could also be based on the operational mass of objects into orbit. Overall, the economics literature highlights that capping the total activity level is more efficient than capping rates and offers a more predictable risk reduction (Boom & Dijkstra, 2009; Schwartz, 2017). While cap-and-trade programs set a price on every unit of risk created, credit trading programs only price the externality above the baseline. As demand increases, regulated actors can increase their overall activity while keeping the required limit on the rate of risk creation per unit of activity. In the space context, if demand for satellite services grows, under a credit trading program, the total amount of debris-related risk creation would not be capped and would grow commensurately. Another drawback of the credit trading program is that it can lead to a rebound effect. The rate-based requirement can incentivize efficiency improvements, which will then prompt more consumption.[9]

[9]For example, when satellite operators reduce the number of debris created while providing a "unit of" service, they can sell credits that allow them to reduce the price of the service. As a

6.1.2.3 Other aspects to be considered

In its recent analysis of market-based mechanisms applied to the space debris context, the Institute for Policy Integrity (2019) raised two aspects that might hamper the effectiveness of marketable permits: non-additionality and the non-consideration of accidental collisions and explosions.

Non-additionality arises when the marketable permit program rewards an actor for an activity that it would have conducted even without the program's existence. In a cap-and-trade system, setting the cap at a lower level than the current total risk creation per period is sufficient to avoid non-additionality. In a credit trading system, non-additionality can be avoided if the performance-based baseline is more stringent than the current debris mitigation practices.

Sources of debris can be grouped into four categories: collisions, explosions, debris released during normal operations, and payloads lost (see § 2.2.1). All of these sources should be encompassed in the marketable permit program. At which moment the incremental debris-related risk is calculated influences which sources can be taken into account. Let us first assume that the risk from newly created debris is computed at a single point in time. For example, permits are required at the end of the year for all newly created debris-related risks during the year. For each piece of debris, the risk and the underlying required number of permits are calculated over the piece of debris' lifetime and not adapted later. Figure 6.1 presents the different channels by which debris are generated and how they are encompassed in the debris-related risk defined in § 6.1.2.1 coupled with this accounting method. Operators would be required to hold permits for debris released during normal operations and payload lost during the year. If one of their operational asset collides with another object or explode, they could also be required to hold permits for the debris created. If debris released during normal operations or payload lost collide or explode at a later time, no additional permit would be required.[10] Nonetheless, the debris-related risk of those objects would have been taken into account in the risk calculation (as the risk depends on the mass). This is not the case for explosions. We could imagine modeling this risk and including it in the debris-related risk creation (i.e., include the probability of explosion in Equation 6.2). When the incremental risk is assessed periodically, the regulator could potentially take into account the collisions and explosions of debris released during normal operations and payloads lost.

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result more units of the service are consumed, which results in more debris generated.

[10]Note that if debris released during normal operations or payloads lost collide or explode before the point in time where permits are required, those could be accounted for.

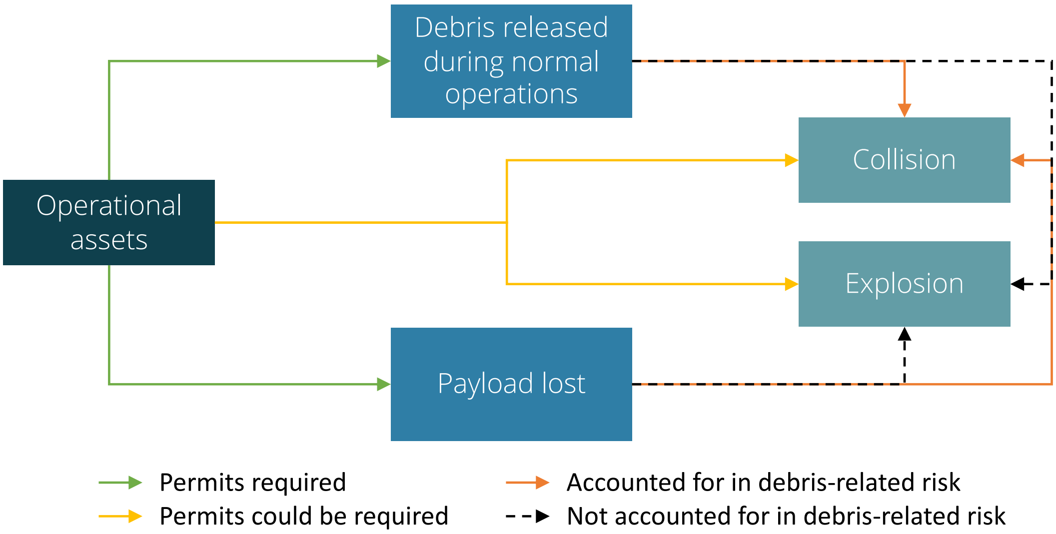

FIGURE 6.1 – Sources of space debris and channels encompassed in a marketable permit scheme with debris-related risk defined in Equation 6.2 and permits required at one point in time for newly created debris.

6.1.3 Marketable permits proposals

Macauley (2003) is one of the first authors to propose the application of marketable permits in the space debris context (her 1994 paper already points in this direction). A few authors have mentioned this policy approach (see, e.g., J. B. Taylor, 2011), but to the best of my knowledge, only Pecujlic and Germann (2015) have developed a concrete marketable permit proposal for space debris. They propose a cap-and-trade scheme with annual caps on the debris emitted during launch activities and the number of inactive payloads in orbit, with national and international caps. The scheme would be divided into three phases. In the first phase, which would last 3 to 5 years, the caps would be set based on best estimates due to the lack of available data. Based on the average number of debris categorized per launch reported by Smirnov (2001), they propose to set the initial cap at "seven categorized objects per launch" (p. 141).[11] There would be no cap on inactive payloads in the first phase. In the second phase, the per launch cap would be reduced to 3–4 objects, depending on the state of technological progress, and a cap on inactive payloads introduced. The latter would depend on the number of existing inactive satellites per state and could start at two-thirds of a country's inactive payloads. In the

[11] It is unclear if the per launch cap is to be multiplied by the number of launches to have a cap-and-trade scheme or if it is a rate-based requirement and thus their proposal is more a credit trading scheme.

third phase, caps would be marginally reduced. In an initial transition period, permits could be issued for free and then would be auctioned. Actors pursuing space activities that result in the creation of space debris would need to "hold permits corresponding to their pollution quote" (Pecujlic & Germann, 2015, p. 142). The enforcement of the scheme would take place both at the national and international levels. Through national legislation, states would make sure that their national actors respect the cap (e.g., using monetary penalties, or reduced allowances). At the international level, countries exceeding their cap would be penalized. Revenues collected through auctions and penalties would be channeled to scientific research and funding of active retrieval of space debris.

6.2 Regulatory fees

Regulatory fees, or Pigouvian taxes, are similar to marketable permits. With both regulation types, rational actors will perform an activity as long as its benefit (marginal revenue) outweighs its marginal cost (including the fee or the purchase of permits). If a regulatory fee per unit of currency is set to F and leads to an amount of this currency of Q, then issuing Q marketable permits would lead to the permit price per unit of currency to reach F (if the permit market is competitive; OECD, 2008). Thus, the level and pattern of activity reduction, as well as the abatement cost incurred by the actors are the same in both regulatory schemes. However, this holds only under the condition of certainty. If the regulator faces uncertainty regarding the abatement costs of the entities regulated, the outcome of these two approaches will differ. Marketable permits ensure that a certain amount of the activity is performed, but at uncertain abatement cost, while a regulatory fee places an upper bound on the abatement cost, but does not guarantee a certain amount of activity performed (see, e.g., Wiener, 1999). A regulatory fee is a per-unit compliance cost that is guaranteed and independent of the amount of activity performed. Firms facing high abatement costs can always opt to pay the fee. If more firms opt for this option than expected by the regulator, the reduction of the activity regulated will not achieve its target. The uncertainty over economic growth can also impede the fee's ability to meet the policy goal, as firms can always choose to pay the fee if demand for their products or services rises.

If enforcement is imperfect, the theory predicts that marketable permits will perform better than regulatory fees (Tietenberg, 2006). If the price of the marketable permit is subject to significant fluctuations, it has been argued that it does not provide a strong enough price signal for long-term capital investment, and thus regulatory fees are preferable in this case (Schwartz, 2017).

A key feature of regulatory fees is that it generates money, which can be used to further the policy goal and provide additional benefits. Note that marketable permits also generate money if they are auctioned.

6.2.1 Regulatory fees in the space debris context

Setting a regulatory fee involves two components: defining the unit of activity regulated that would drive fee liability and setting an efficient fee level (Institute for Policy Integrity, 2019). The considerations on designing a currency for a marketable permit scheme (see discussion in § 6.1.2.1) also applies in defining the unit of risk for a regulatory fee. Similarly to the marketable permit program, the regulatory authority must be able to monitor and verify increases in the unit of risk. Moreover, it must be able to tie new units of risk created to the actors responsible for their creation, as the negative externality must be internalized by the actor responsible for it. Determining the efficient fee level is difficult as the regulatory authority is lacking information regarding the current and future abatement costs of the regulated actors. For example, in the near future, services to actively remove derelict satellites will be available, but a significant uncertainty regarding their cost remains (see discussion in Appendix C). Knowledge about the cost of de-orbiting a failed satellite would help the regulatory authority to price the fee efficiently. To justify the fee level, the regulatory authority would also have to take into account the cost of risks created by unmitigated debris.

An important point is what is the trigger of the fee payment. Would regulated actors be required to pay the fee ex-ante based on disclosures of the predicted amount of debris-related risk created by their mission? Or would the fee be triggered on an ongoing basis based on the actual in-orbit debris created? In the next section, I review the different regulatory fee mechanisms proposed in the literature, along with the recycling schemes proposed. I then discuss which one would work best.

6.2.2 Regulatory fees proposals

Different forms of regulatory fees, often tied to a recycling mechanism, have been proposed in the literature. However, most of them are only developed at the abstract level and do not provide details on how they would be implemented. In particular, discussions about the unit of risk driving the fee, the trigger of the fee liability, and the enforcement mechanism are lacking. I review those proposals below.

Scheraga (1986) is one of the first to propose the introduction of a Pigouvian tax to bring the marginal cost of debris creation to its marginal social cost level. He notes two difficulties in implementing such a tax: measuring the amount of pollution created by states and setting the appropriate tax level per unit of pollution. For the latter, he argues that the correct level can be identified through experimentation, which will yield the necessary information on the cost and benefits of pollution abatement. The biggest impediment to the implementation of such a tax identified by Scheraga (1986)—the monitoring difficulty—has, thanks to technological innovation, been largely alleviated.

In 1992, Roberts proposed a "liability pool" to curb the problem of space debris. In its proposal, each entity willing to send an object into orbit would have to pay a fee commensurate to the estimated harm the object would cause on the space environment. When damage would occur, payments from the pool would compensate the victims. As a non-negligible amount of risk was already present at that time, Roberts (1992) proposed to use retroactive payments (i.e., on prior use of outer space) to ensure sufficient funding of the pool. A similar proposal has been made by Dunstan and Szoka (2009). Operators would pay small fees to their governments, which would then contribute to an international "Orbital Debris Removal and Recycling Fund." This fund would be used to pay bounties to private companies that successfully remove orbital debris. Each piece of debris would be priced according to the risk it causes to the space environment. The change of focus for the recycling mechanism between Roberts (1992) and Dunstan and Szoka (2009) underlines the maturation of retrieval technologies and the growing risk perception of space debris. Compensating potential victims is no longer the focus; preventing a cascade of collisions to happen takes center stage.

Limperis (1998) described a per launch taxation proposal made in an unpublished student note. The number of authorized debris created per launch would be caped, and any party exceeding this cap would face a non-compliance fee. The note also suggests the assessment of a fee on any launch. The revenues of the fee would be pooled and used to fund "scientific research and [the] development of technology to eliminate launch debris and cleanup existing orbital debris" (Limperis, 1998, p. 337).

The idea of an orbital use tax has been developed by numerous authors (e.g., Akers, 2012; Evans & Arakawa, 2012; Garber, 2017; Macauley, 2003; Pusey, 2010; Williamson, 2006), albeit abstractly. The mandatory fee would be levied before launch to fund SSA, retrieval technology research and development, and orbital clean up. This tax would be analogous to other taxes levied to fund infrastructure maintenance on Earth (e.g., yearly fees for highway use in Switzerland or the US). Most authors do not discuss the driver of the fee level. Macauley (2003) proposes a fee levied on the debris generation potential of space missions with discounts for risk-reducing design features or operating practices, while Pusey (2010) suggests that the tax could vary based on the mitigation practices implemented by the operators. Akers (2012) argues that the tax could be modeled after California's Electronic Waste Recycling Fee. The state imposes a recycling fee on specified electronic devices and uses the proceeds to fund the environmentally safe disposal of hazardous materials found in those devices. Taking this model for space debris overlooks one major difference: consumers cannot help in ensuring the safe disposal of hazardous material, but operators can directly influence the safe disposal of their spacecraft. The recycling fee model applied to space debris would either totally transfer the cleaning burden to the state or would need to be coupled with command-and-control regulation. Such fees would give the operators the impression that they have paid for the disposal of their spacecraft and that they no longer need to take care of it. It is exactly the opposite incentive that regulation should promote. Some authors mention that an orbital use tax could include a deposit and refund mechanism (Evans & Arakawa, 2012; Garber, 2017; Macauley, 2003). Operators would have to deposit the fee before the launch and would be refunded in whole or in part after successful PMD of their spacecraft.

6.2.3 An efficient and effective fee mechanism

Proposals that involve a simple unit of activity regulated (e.g., tax per launch, or per spacecraft launched) are easy to administer but imperfectly internalize the cost operators impose on others when conducting space activities. This results in effectiveness and efficiency losses. The fee must be tied to actual risk creation to incentivize its reduction. This can be achieved through modeling of the risk increase due to the creation of a new piece of debris, or through a proxy formula of this modeling (see discussion in § 6.1.2.1).

Carroll (2019) notes that currently the only mechanism to limit debris creation is prospective—through licensing—but PMD reliability claims cannot be proven ex-ante. Satellites can be lost due to collision with untracked debris, or due to malfunctioning. Operators can also go bankrupt, leaving their assets idle in space. Those observations should inform the fee mechanism. Actual debris creation must be the driver of the fee, but the mechanism must ensure that it is paid when it is due. A constellation operator going bankrupt could leave hundreds of satellites orbiting the Earth for hundreds of years without paying any fees. The best option available to prevent such an outcome is a deposit and refund scheme, which bases the fee on actual risk creation but requires payment ex-ante to prevent non-payment. Satellite operators would be required to pay a fee before the launch of their satellites commensurate with the risk increase that could result from losing them. When operators show that they successfully performed the PMD, the fee would be wholly refunded.[12] The regulator would retain part of the fee if some debris-related risk were created during on-orbit operations. The main disadvantage of this method is that it would require operators to pay a large sum to the regulator before launching their assets, i.e., prior to any revenue. Given that new space endeavors such as communication constellations are capital intensive, requiring a large fee payment before the launch might be unbearable for the operators.[13] A second option is to require the fee payment on a periodical basis. All risks created during a period (e.g., a year) would result in a fee payment at the end of the period. This reduces the risk of non-payment but not entirely. In case of bankruptcy, the operator might be unable to pay for the risk created by its assets. However, a periodic fee would strongly incentivize the removal of the debris triggering the fee. A third option is to combine the two methods, allowing to reduce the ex-ante payment but still keeping some money available to lessen the risk that an operator might be unable to pay the fee for the risk it created.

The most concrete example of a deposit and refund scheme is the FCC's recent proposal in its FNPRM of a "performance bond for successful disposal" (R&O and FNPRM, 2020, p. 90).[14] The FCC proposes that the amount of the bond B (in USD) should be

$$B = M_T \cdot (Y - 25) \cdot O_T, \tag{6.4}$$

where M_T is the total mass of the satellite system in kilograms, Y is the number of years a failed satellite would remain in orbit, and O_T is the total number of objects in orbit. The FCC suggests that this amount could be capped, e.g., at USD 100 M. From Equation 6.4, we see that any satellite system with a predicted lifetime smaller than 25 years will not require the payment of a bond. For example, an operator would pay for a single 1-ton satellite USD 1,000 per predicted year in orbit above 25 years. For a OneWeb-like constellation this would be USD 14.6 M per predicted year in orbit above 25 years.[15] At their 1,200 km altitude, the OneWeb-like satellites have a predicted lifetime in the thousands of years. This

[12] It could also be partially refunded, leaving some money to the regulator to fund research and development in debris remediation and SSA.

[13] OneWeb recently filed for chapter 11 bankruptcy as it was not able to secure enough funding to terminate the launch of its constellation (OneWeb, 2020a). This event highlights that LEO constellations are already hard to finance, and an additional financial burden might make their financing even more difficult. However, at the same time, stronger space debris regulation can lower the risk of this type of venture and attract investment.

[14] Note that the FCC's proposal is a surety bond that does not require to 'deposit' the value of the bond. A surety provider guarantees against a fee that the operator will meet the terms agreed upon with the regulator. However, the discussion also applies to a mechanism with a deposit.

[15] I assume 648 spacecraft with a weight of 150 kg each.

example highlights that this formula could only be implemented with a cap for large systems. Otherwise, the required amount would be unbearable for operators. The method to calculate the predicted lifetime is not specified in the FNPRM but should be the same for all licensees.

Depending on the number and mass of undisposed objects at the end of a license term, a share of the bond would be forfeited. The FCC proposes that the forfeited amount F could be

$$F = (M_{TU} - M_{EU}) \cdot (Y - 25) \cdot (O_{TU} - O_{EU}), \tag{6.5}$$

where M_{TU} is the total undisposed mass in orbit in kilograms, M_{EU} is the expected undisposed mass in orbit in kilograms, Y is the mean of the remaining years in orbit for any individual undisposed object (capped at a maximum of 200 years per object), O_{TU} is the total number of undisposed objects in orbit, and O_{EU} is the expected number of undisposed objects in orbit. Expected values for the number and masses of undisposed objects are derived from the licensee's calculation of the probability of successful disposal (or any planned debris release). The forfeited amount accounts for undisposed objects which were not 'planned' in the license. For example, if a OneWeb-like constellation had obtained its license touting a 90% PMD success rate but achieved only 85%, then the operator would have to pay about USD 27 M.[16] Note that this amount would likely not cover the cost of actively removing the 32 lost spacecraft in the near-term. The FCC proposal does not specify the outcome in case of an explosion or collision of one of the licensed spacecraft. However, as any collision or explosion generates undisposed objects, they can be accounted for in Equation 6.5.

With such a scheme, operators would have a strong monetary incentive to make everything possible to achieve the PMD of their spacecraft and to avoid the creation of any unplanned debris.[17] Some commentators to the FCC's NPRM dismiss this incentive. For example, Eutelsat argues that "satellite end-of-life anomalies are typically a result of unanticipated events that occur despite a proponent's best effort, and collection under a performance bond does not mitigate the results of such anomalies" (Eutelsat, Reply Comment, 2019, p. 4). However, space actors do not have an incentive to make their "best effort" for a successful PMD (see § 3.2) and take the necessary steps to reduce the probability of unanticipated events. The bond also alleviates the enforcement problem of ex-ante requirements. The formula

[16] See footnote 15. The lifetime of the spacecraft lost is greater than 200 and thus $Y = 200$.

[17] Note that given the definition of the forfeited amount proposed by the FCC (Equation 6.5), the expected undisposed mass and number of objects 'planned' in the license should be kept low for this instrument to be effective in reducing debris creation. For example, for large constellations this still means requiring a high PMD reliability.

for the forfeited amount (Equation 6.5) is an example of a proxy measure of debris-related risk creation. For simplicity, it does not take into account the collision risk of undisposed objects which would require modeling,[18] but encompass the number, mass, and lifetime of undisposed objects. To which extent this simplification result in the leak of the externality should be analyzed through modeling. The proxy formula for F could also be used to calculate a periodic regulatory fee. However, as not all undisposed objects trigger a fee payment, its ongoing payment is more challenging.

If the amount B must be deposited prior to launch or the surety bond mechanism in place requires large fee payments, one might envision reducing the amount of the bond B but requiring an ongoing fee payment once F becomes greater than zero. I give more detail about this proposal and analyze the impact of such a scheme through an example in Appendix E.

Garber (2017) argues that even if a suitable tax could be devised, it could only be applied to the commercial sector, as "the government taxing itself certainly raises some thorny issues." If the recycling mechanism of the fee is clearly defined, then I do not see any impediments in taxing governmental activities in the same way as commercial ones are. The benefits of governmental activities would then be weighed against their social cost and not their "private" cost. At the same time, the money collected when the government fines itself would be channeled to a defined purpose (e.g., space debris clean up).

In a first phase, the money collected through the fee should be used to fund research and development of remediation technologies. In a second phase, the money should be used to fund debris retrieval directly. As it is not the government's role to conduct this activity, private companies should be hired. We should assign relative values to all pieces of debris and let the bounty hunters choose the targets that provide the highest net benefits given their retrieval method (Carroll, 2019). This is technology agnostic and would foster innovation where it provides the best cost-benefit ratios. Carroll (2019) argues that the bounty should not only encompass retrieval but any activity that quantifiably reduce future estimated debris costs (e.g., JCA, orbital data updating to improve a conjunction warning, finding small debris at dense altitudes to provide tracking).[19]

[18]Without modeling, we could re-scale B and F depending on the density of objects able to cause a catastrophic collision (this would require using a statistical distribution as not all object able to result in a catastrophic collision are tracked). In B, we would take this debris density at the planned altitude of the satellites. In F, we would take the mean of the debris density at the altitudes of the undisposed objects.

[19]Carroll (2019) develops the essential features such a bounty program could have and a bounty calculation method.

6.3 Insurance markets

In general, insurance has three functions (Abraham, 1988): transferring risk from relatively risk-averse parties to more risk-seeking ones, spreading risk by pooling individual risks, and allocating (i.e., identifying) risks. The latter is performed by insurers who charge premiums that reflect the risk level of the insured parties. These functions can be performed effectively under certain conditions of uncertainty and are undermined by information asymmetries (i.e., when the insured has more information than the insurer). To perform efficiently, insurers must have access to accurate information to estimate ex-ante the probability that the insured event will occur and the magnitude of its economic consequences (OECD, 2003). Such information is necessary to compute an actuarially fair premium. In other words, insurance can deal with risk, or predictable probabilities, but not with uncertainty, or unpredictable probability of loss (Knight, 1921).

6.3.1 Insurance markets as surrogate regulation

6.3.1.1 Monitoring and bonding devices create safety incentives

Under the condition of asymmetrical information between the insured and the insurers, two problems can arise: adverse selection and moral hazard (see, e.g., T. Baker, 1996; Pauly, 1968, 1974; Shavell, 1979). When insurance applicants possess more information than the insurer, applicants can select only the coverages that they would most likely need. Thus, an adverse selection process occurs where a disproportionate number of high-risk applicants seek coverage, and low-risk parties drop out. If an insurer is not able to obtain relevant information about changes in the risk posed by insureds once they have contracted insurance, the policyholders have a diminished incentive to avoid losses (e.g., by taking preventive measures). The moral hazard is the insured's indifference to losses due to the existence of insurance. Adverse selection and moral hazard are types of agency costs. When two parties have diverging interests and the agent (the insurer) has more information than the principal (the insured), the latter cannot ensure that the agent is always acting in its best interest. To align the interests of the principal and the agent, and thus mitigate agency costs, insurers can use a variety of monitoring and bonding devices (see, e.g., Arrow, 1971; Hölmstrom, 1979). Monitoring is aimed primarily at controlling the insured's behavior, while bonding's purpose is to limit interest divergence between the insurer and the insured. Monitoring and bonding devices ensure the profitability of the insurers by enabling an effective spreading and allocation of risk. At the same time, they create safety incentives for the insureds. Three mechanisms are commonly used in insurance to alleviate the information asymmetries and ensure a correct risk allocation (Abraham, 1988):

1. *Risk classification:* Insurers must perform risk classification to ensure they offer a competitive price on the market. At the same time, this classification can incentivize insureds to reduce their risk exposure. Two forms of classification (which are often combined) are generally employed: feature and experience rating. Feature rating consists of taking into account objective features of the insured's operation (which are proxy measures of its risk exposure) to derive its premium. Experience rating bases premiums on the loss experience (in a given period) of the insured. Feature rating incentivizes risk reduction if the marginal saving in premiums that would result from modifying the features on which premiums are based is greater than the cost of the modification. However, if the insured cannot or is not willing to control the variables on which the premium is based, feature rating does not result in risk reduction. Feature rating can also bring valuable information to the insureds as it indicates to them which features of their activities affect the level of risk posed by those activities. In comparison, experience rating takes into account the past operations and the insured's loss experience to derive premiums. Thus, it does not provide information to the insured regarding the features of its activities relevant to risk reduction. However, this risk classification methodology always creates an incentive for the insured to reduce its risk exposure, as a reduction of losses will reduce premiums. Both risk classification can influence the level of the activity insured. Feature rating based on features tied to the level of activity (e.g., gross sales) may have an impact on the amount of activity performed, while experience rating creates an incentive to optimize the activity as this is a key variable influencing the loss experience.

2. *Deductibles and policy exclusions:* To ensure a policyholder keeps an incentive in reducing risk once it has contracted an insurance policy, deductibles and policy exclusions can be used. Deductibles are intended to align the interest of the agent and the principal, by requiring the principal to have a stake. In case of a loss, the insured would also suffer. To effectively mitigate the moral hazard, the greater the moral hazard is in the absence of a deductible, the larger the deductible should be. Policy exclusions also incentivize safety by excluding certain types of losses or losses caused by certain kinds of behavior from the insurance policy. Often, losses caused intentionally by the insured

are excluded.

3. *Surrogate regulation:* Monitoring and bonding activities performed by insurers create safety incentives for insureds and thus act as "surrogate regulations." Those activities are similar to setting standards and enforcing them, thus resembling a command-and-control regulation. The risk assessment and risk management processes can yield further risk reduction incentives. If a positive risk assessment is a prerequisite to obtain insurance, the insureds have further incentives to reduce their risk exposure. Codification of the risk assessment requirements is equivalent to private standard-setting. Risk management ensures continuous motivation for the insured to take safety measures. The threat of cancellation, non-renewal, or reclassification upon the expiration of the coverage create incentives for the insured to follow the insurer's recommendations. Overall, risk assessment and management can have the same behavioral impact as traditional regulation, as the insurer can impose costs to the insured commensurate to its risk-taking behavior. The ability of insurance to act as a surrogate regulation is especially true in contexts where proof of liability insurance coverage is a prerequisite to obtaining a license.

The safety incentives created by the insurance industry are not only a byproduct of the attempt at reducing the information asymmetry to ensure a correct risk allocation but are also genuinely in the interest of the insurers. By reducing risk, insurers make premiums more affordable and thus increase the market size. In a competitive market, their ability to identify cheap risk-reducing measures (which their clients must adhere to) is critical in developing a competitive advantage and lowering their premiums. Moreover, once a policy is issued, insurers benefit from adherence to risk-reducing practices.

6.3.1.2 Insurance can replace governmental regulations

Insurers act as safety regulators in a variety of contexts such as vehicle, homeowner, and environmental liability insurance (see detailed examples in Ben-Shahar & Logue, 2012). By adopting some of the quasi-regulatory mechanisms mentioned in § 6.3.1.1, insurers replace or complement regulation enacted by governments. However, in some domains, insurers cannot take this role (Ben-Shahar & Logue, 2012). First, they are not well suited to completely stop an activity or behavior, as some regulatory tools are only available to the government. A regulatory agency can use the threat of criminal sanctions and the police to stop actions physically. Second, some risks are not insurable (e.g., "known unknowns"[20] such as terrorist attacks, correlated risks; Boardman, 2005) and thus are only regulated by governments. Third, when insurers cannot reap the benefits from their activities to improve safety to reduce insurance costs, governments are more likely to regulate. Indeed, market failure can also occur in the insurance industry. If insurers face an externality, there will be an underprovision of regulation. The production of knowledge, and future and latent harms are examples of such externalities. When developing safety standards, insurers cannot prevent the competition from using them. Insurers' efforts to mitigate risks can reduce future harms, which will benefit future insurers. In the case of latent harms, such as climate change, the damage costs are spread across many entities or individuals not covered by the present insurers. The coordination problem in the case of international latent harm is not only faced by insurers but also by governments; climate change is the prime example. Ben-Shahar and Logue (2012) argue that insurers have a relative advantage in this case. Individuals facing the risk of incurring costs (e.g., damage to their property) are demanding insurance services. If climate change increases the risk of those costs occurring (e.g., severe weather), individuals will have to pay higher premiums. The increased cost of insurance pushes individuals to ask more stringent policies from the government. At the same time, insurers look for risk-reducing measures to lower their premiums (Kunreuther & Michel-Kerjan, 2007).

Ben-Shahar and Logue (2012) argue that private insurance markets can and sometimes do outperform governments. The main argument to support this claim is that insurers have privileged access to information, that they face competition, and that private contracting enables insurers to monitor safety in ways not accessible to governments. Compared to command-and-control regulations, which often require specific safety thresholds to be met, insurers can offer different safety options that the insureds can choose from depending on the cost of the respective measures and their associated premiums reduction. This ex-ante premium adjustment mechanism is more efficient than requiring a uniform safety level. Governments can use Pigouvian taxes to obtain a result similar to differentiated premiums. However, insurers are better placed to price the externality than governments, as they have informational and administrative advantages. Insurers have access to more detailed data on features and past experience of their customers. Governments are not insuring the externality and thus do not have to bear the cost of inaccurately calculating it. The loss of profit insurers would suffer from inaccurate premium pricing give them an incentive to collect accurate and relevant information that governments do not have. The monitoring of activities is necessary to implement safety standards. Government agencies usually monitor compliance to a standard

[20] Contingencies which we are aware of, but to which neither a probability of occurrence nor a magnitude of damage can be actuarially calculated.

ex-ante, but such monitoring can also happen ex-post after harm occurs (e.g., through courts). Insurers' monitoring can be more efficient, as it is performed continuously and using technologies and practices that the government lacks. Here again, competition gives an incentive for thorough monitoring that is absent when it is performed by regulatory agencies.

6.3.2 Insurance markets in the space debris context

Two types of satellite insurance are available on the market: first-party (property) and third-party liability (TPL) insurance. Both types of insurance can be bought for launch, in-orbit operations, or both. Satellite first-party insurance insures against the loss of performance of a satellite (i.e., it insures the asset),[21] while TPL insurance insures against damage caused by a space operator's asset to third-parties.

I first look at the property insurance market for satellites and evaluate its ability to incentivize risk-reducing behaviors in § 6.3.2.1. In § 6.3.2.2, I look at the current TPL insurance market for space assets. I show why the conditions for liability insurance to act as a surrogate regulation are not present and discuss what steps should be taken to provide the necessary conditions. Finally, I discuss another type of insurance that would provide for the de-orbiting of the insured spacecraft in case of a failure in § 6.3.2.3.

6.3.2.1 First-party insurance

In space, first-party insurance is more common than TPL insurance. Operators often cover the risk of losing their satellites during the launch and the first months of operations (up to a year). In-orbit first-party insurance can then be bought on a yearly basis. The top panel of Figure 6.2 shows the share of satellites currently covered by property insurance in LEO and GEO. About half the satellites in GEO are insured for a total value of USD 27.2 B, while only a tiny fraction of the satellites in LEO are insured for a total value of USD 4.2 B (as of February 2020;

[21]The loss of performance can be complete (total damage), e.g., in case of a rocket failure, the loss of the spacecraft in orbit, or a catastrophic collision, or incomplete (partial loss), e.g., in case of incorrect placement in orbit affecting the satellite's performances, sub-systems malfunctions in orbit, or a non-lethal collision.

Kunstadter, 2020).[22] The value insured is generally the book value of the satellite and the launch, but sometimes the value is based on revenues (the amount covered is agreed before signing the policy). First-party insurance policies cover "all risks," unless excluded. Although the probability of a collision with a piece of space debris in LEO has significantly increased in the past twenty years, this probability is still about two orders of magnitude smaller than the one of technical failure. As collision probability accounts for a small share of the overall probability of losing a spacecraft, premium rates are not driven by collision probabilities (Secure World Foundation, 2019). The market capacity drives the premiums, not the operational experience. As shown on the bottom panel of Figure 6.2, after the 2007 Chinese ASAT test and the 2009 Iridium-Cosmos collision, premium rates did not increase. Debris-related risks would have to increase drastically to impact the premium rates significantly and incentivize risk-reducing behaviors.

As collisions with untrackable pieces of debris can lead to the loss of a satellite, insurers have an incentive to reduce the generation of such debris. However, they face an externality. The efforts they put in inducing their clients to implement risk-mitigating measures not only benefit them but other insurers. This results in an underprovision of these measures. As penalizing their clients for non-compliance with space debris mitigation guidelines does not improve their risk classification but decreases their competitiveness, insurers are, for the moment, unwilling to take steps. Insurers encourage operators to follow best practices and international guidelines, but neither require compliance nor penalize them economically for non-compliance.

Looking at the premium rates and the capacity of the market on the bottom panel of Figure 6.2, it appears that as capacity increases, premium rates decrease. The capacity is directly tied to insurers' experience and the attractiveness of the market. The global economic context (low-interest rates) and the favorable premiums-to-claims ratio have led to an increase in capacity and resulted in low premiums making the space insurance market a buyer's market (Aon Risk Solutions, 2016). In a soft insurance market, insurers have only a limited pricing power, and few direct interactions with their clients as most of them go through a broker (Samson et al., 2018).

[22] Note that generally, governments do not insure their satellites. The growth of commercial activities should result in the growth of the share of satellites insured. However, constellations often manage risk using in-orbit spares rather than by purchasing insurance. The launch of megaconstellations could thus reduce the share of satellites insured.

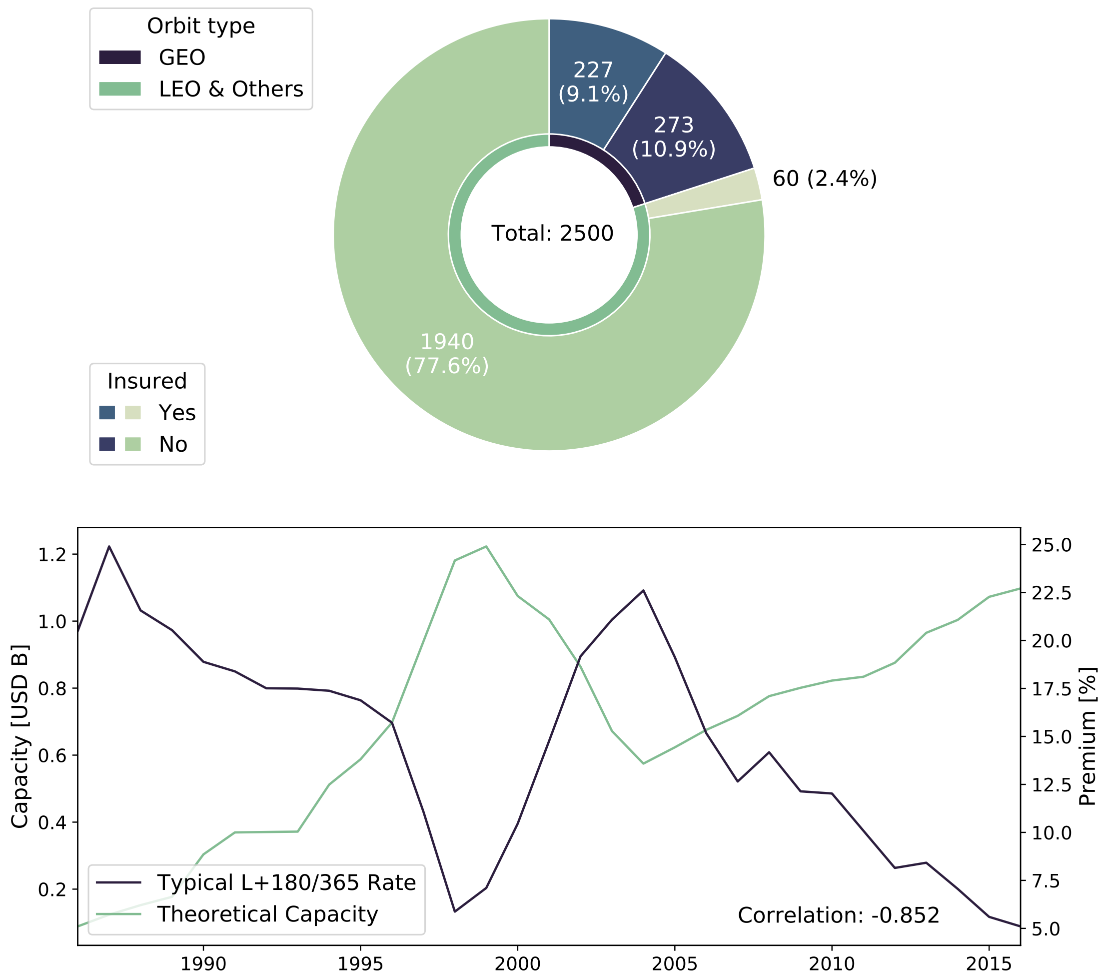

FIGURE 6.2 – *Top panel:* Number and share of satellites insured (first-party insurance) by orbit types as of February 2020. The value insured is USD 27.2 B for GEO and USD 4.2 B for LEO (adapted from an AXA XL presentation; Kunstadter, 2020). *Bottom panel:* Theoretical capacity of the insurance market and typical premium rates for a launch plus 180/365 days insurance. Capacity and premiums are negatively correlated (adapted from Aon Risk Solutions, 2016).

6.3.2.2 Third-party liability insurance

Under the Liability Convention (1971, Articles II–III), a launching state is *strictly liable* for damage caused by its space object on the surface of the Earth or to aircraft in flight, but is liable for damage caused in orbit only if the damage is due to its *fault* or the fault of persons for whom it is responsible (see § 4.1.2). Due to the strong liability regime for damage on the ground or to aircraft in flight, launching states often require operators to purchase a TPL insurance for launch and/or reentry. As the likelihood of a claim is lower for in-orbit activities, due to the fault-based regime, not all major launching states require an in-orbit TPL insurance. For example, while the US does not require an in-orbit TPL, France, the UK, and Japan require it (with varying limit and scope). In what follows, the focus of the discussion is on in-orbit TPL as launch TPL cannot affect in-orbit behavior.

Data on the number of satellites covered by in-orbit TPL insurance is lacking.[23] According to a space insurer, major GEO fleet operators and LEO constellation operators Planet Labs and Iridium hold in-orbit TPL. It remains unclear which share of the TPL policyholders purchased the insurance voluntarily and which share purchased it because it was required to obtain a license.

As we have seen, a well-functioning liability insurance market can be, under certain conditions, an alternative to regulations. Would this approach be efficient and effective in the context of space debris? A prerequisite for insurance markets to achieve their risk-reduction potential is the availability of a clear legal framework regarding liability rules. As previously discussed in § 4.1.2, the international legal framework regulating activities in space is plagued with numerous uncertainties, especially regarding space debris. The content of the treaties is subject to interpretation, and the absence of legal precedent leaves numerous points uncertain. As the premium rates are priced according to the risk of a claim, and not the probability of a collision, if the likelihood of a claim in case of a collision is low, then the pricing mechanism of TPL insurance premium rates cannot induce risk-reducing behaviors. The historical absence of claims for TPL impedes the pricing of insurance premium rates commensurately with the collision probability. Although some risk classification is performed to price TPL insurance, premiums appear to be mostly driven by the cost of capital. This precludes TPL insurance from acting as a surrogate regulation.

[23] In LEO, only 3% of the satellites have a first-party insurance (see top panel of Figure 6.2). However, it is hard to draw conclusions from this regarding in-orbit TPL as both satellites covered and not covered by a first-party insurance hold TPL insurance.

6.3. Insurance markets

Even with a more certain legal framework and efficient enforcement mechanisms, the remote nature of space would still render the assertion of liability difficult. Determining from the ground if a spacecraft has been lost due to a technical failure or due to a collision with space debris is often not possible. The uncertain legal framework and the remote nature of space have led the space industry to rely on first-party insurance, which provides coverage for "all risks," rather than TPL. First-party insurance offers a much quicker and easier solution for operators than TPL when they lose an asset. TPL is thus likely to function at best inefficiently as an operator whose insured space asset is damaged by a piece of space debris will be indemnified by its insurer. The latter cannot recover the amount by suing the entity responsible for the damage as space insurance policies contain a waiver of recourse. However, the first-party insurance only covers the book value of the satellite lost (including launch), but the damages could include, e.g., reputation deficit and loss of customers. As the first-party insurance does not cover those damages, the operator might still seek indemnification through courts or its launching state (i.e., through international treaties; see § 4.1.4).

Information is required by insurance companies to allocate risk effectively and thus align their interests with those of the insureds. To perform risk classification using experience rating, insurers need data on the loss experience of the applicants. As insurers have faced no TPL claim yet, data on loss experience is lacking. The use of feature rating is subject to the uncertainty regarding what constitutes proper behavior in space. There are no commonly agreed rules of conduct in space. Thus insurers do not have a benchmark to rate the applicants' operations and punish them financially for not respecting the rules (Samson et al., 2018). The development of a Space Sustainability Rating by the World Economic Forum (WEF) Global Future Council on Space Technologies (Foust, 2020; World Economic Forum, n.d.) could provide the necessary standards and methodologies to assess operators' behavior in space and the risk they pose to the space environment.

Requiring operators to hold in-orbit TPL insurance cannot incentivize them to reduce the amount of debris generated due to the decoupling between risk and premium rates. However, if such a requirement applies as long as a satellite is in orbit, this would act as a kind of orbital fee, incentivizing the timely de-orbit of spacecraft (see, e.g., Reesman et al., 2020). It would incentivize operators to take less risk once a technical failure occurs or when extending the life of a spacecraft. From the perspective of the regulator, this requirement is easier to implement than an orbital fee. Also, it does not require the regulator to price and justify the pricing of the fee. However, contrary to a fee, this mechanism would not provide funds for actively removing spacecraft. Moreover, it would imperfectly internalize the externality as it would not result in a fee level commensurate with risk, and debris released during normal operations would probably not be accounted for.

6.3.2.3 De-orbiting insurance

An alternative to the TPL insurance is a "de-orbiting insurance." Instead of providing compensation for damage caused by the object insured, it would provide for the spacecraft's de-orbiting if it fails (Anzaldua & Dunlop, 2015). If a PMD failure were to occur, the insurer would purchase the service to dispose (or even rehabilitate, depending on the state of the technology) the failed satellite against a premium. Through risk classification, insurers could differentiate premiums to reflect the risk of PMD failure posed by different space missions. This would create an incentive for operators to maximize their PMD success, resulting in an efficient policy mechanism. For such insurance products to exist, commercial defunct satellite retrieval services would need to be available (which is conceivable in the near future), and regulations would have to economically penalize the failure to de-orbit a spacecraft (e.g., through a fee or a forfeited bond). One could imagine only requiring operators to hold a de-orbiting insurance without penalization for non-compliance with de-orbit requirements. However, this would result in a moral hazard problem. Once operators have bought this insurance, they no longer have an incentive to de-orbit their spacecraft. Interests of the insureds and insurers diverge, as insurers would like spacecraft to be de-orbited the sooner possible, while operators would like to keep them in orbit the longer possible to increase their revenues. Insurers cannot perfectly monitor the insureds' behavior, and thus such insurance would either be prohibitively expensive to compensate for the moral hazard or not offered. This type of insurance could work only to cover the financial risks associated with a failed PMD due to a penalty imposed by the regulator, as otherwise, operators are not affected by a failed PMD. Thus, this is not a tool that incentivizes de-orbit, but it could nonetheless ease the implementation of regulations that financially penalize operators for PMD failure.

6.4 Market-share liability

Market-share liability is a legal doctrine designed to apportion responsibility based on the respective contribution to a dangerous situation when it is not possible to tie a particular party to the harm caused (see, e.g., Sundahl, 2000, for a brief history of market-share liability). The Supreme Court of California devised this doctrine of liability in *Sindell v. Abbott Laboratories* (1980). In this tort case, plaintiffs sought damages against the manufacturers of diethylstilbesterol (DES), a synthetic form of estrogen. This medicine was administered to pregnant women to prevent miscarriage, but it was later discovered that it could cause vaginal and cervical cancer to their daughters. As DES is fungible and was manufactured by more than 200 companies, victims were unable to identify which manufacturer had produced the medicine taken by their mothers. In similar cases, other courts ruled in favor of the DES manufacturer as the causal link between the plaintiff and a particular manufacturer could not be established. The Supreme Court of California argued that the ever-increasing existence of fungible products in the marketplace called for a new theory of liability that would enable victims to seek compensation without requiring them to identify the specific party responsible for the harm caused. Under this new theory of liability, each DES manufacturer that could have caused the harm would be liable in proportion to its share of the DES market. A manufacturer could exculpate itself by showing that its product could not have caused the harm. Since this case, the use of the market-share liability principle has been embraced by other courts in the DES and other contexts, albeit infrequently. Truly fungible products are rare, and thus, extending this doctrine in other contexts is difficult (Nace, 1991).

6.4.1 Market-share liability in the space debris context

The idea of using market-share liability in the space debris context has been suggested by different authors (see, e.g., Limperis, 1998; Muñoz-Patchen, 2018; Reynolds & Merges, 1989; Sundahl, 2000). The rationale for using this doctrine in the space debris context is the similarities with the case deliberated in *Sindell*: for debris which is either untrackable or unidentifiable,[24] fault cannot be attributed; space debris is relatively fungible; and information regarding the "market shares," the amount of debris generated by the space actors, is available. The use of this doctrine is usually thought of as an extension of the liability defined in the Liability Convention to offer compensation for damage caused by unidentifiable debris. In the occurrence of a collision between an operational spacecraft and an unidentifiable piece of orbital debris, the apportionment of liability and compensation among the spacefaring states would be proportional to each state's contribution to the total space debris population. With this mechanism, victims no longer need to prove causation by a specific state, which would not be possible for unidentifiable debris.

This mechanism has always been referred to as market-share liability by its proponents, but, as pointed out by Rostron (2004), this term is misleading. The proposition involves more of a proportional-share liability based on something

[24]Some tracked pieces of debris cannot be linked to an owner and are thus unidentifiable, while all untrackable pieces of debris are unidentifiable.

different than market shares. As their name suggests, no information on the shares of unidentifiable debris is available. Thus, we have to rely on a proxy. The closest available data is the share of trackable and identifiable orbital debris, but how correlated are the unidentifiable and identifiable debris populations? While Rostron (2004) is concerned that the population of identifiable debris might not be representative of the population of unidentifiable debris, Muñoz-Patchen (2018, p. 256–257) believes that "there is fairly accurate information from the U.N., including registry, sampling, mathematical models, and other records of known collisions and the resultant debris." We can probably assume that given the information available, including the collision and explosion history of each spacefaring nation, and using modeling, we can calculate relatively precisely the national shares of the unidentifiable debris population. Although representing more accurately the risk each nation is causing, this method (hereafter "modeled market-shares") has a different impact on the incentives than the one using the "identifiable market-shares," as we shall see below.

Sundahl (2000) points out that in *Sindell*, the court was concerned that the exact market-share calculation was not possible and that it could lead to an unfair apportionment of liability. However, the court decided that the risk of unfairness using the market-share liability theory was no greater than when a jury has to determine liability in cases involving comparative negligence. Sundahl (2000) concludes that in the case of space debris, each state's contribution can be calculated with acceptable accuracy (i.e., that the unidentifiable and identifiable populations of debris are sufficiently correlated) to apply market-share liability.

An overlooked issue in applying market-share liability in the space debris context is the question of fungibility. Even if we can derive each nation's share of unidentifiable debris accurately, the latter are not fungible.[25] One would want to compute the underlying risk posed by each nation's unidentifiable debris to apportion liability rather than rely on the number (or any other single physical characteristic) of those objects. The imperfect fungibility of space debris does not prevent the use of market-share liability. However, it requires a more complex calculation of each nation's unidentifiable debris-related risk (see discussion in § 6.1.2.1). For the identifiable market-shares method, there is no way to fix the shares to account for the non-fungibility of unidentifiable space debris. In contrast, the modeled market-shares described above could take into account the unidentifiable debris-related risk instead of the numbers of objects.

A second issue not addressed in the literature is to which damage the market-share liability theory would apply. If we are unable to identify a piece of debris, we

[25] For example, one would want to exclude unidentifiable debris which is too small to damage shielded spacecraft.

are potentially also unable to identify that it is the cause of damage. Spacecraft are lost due to numerous factors, including collision with space debris. From the ground, there is often no way to tell if a spacecraft has been lost due to a collision with a piece of debris, a meteoroid, or due to malfunctioning. Could any operator losing its spacecraft claim compensation? What would be the minimum criteria to trigger compensation? Requiring operators to prove that their spacecraft has hit a piece of orbital debris would probably render the market-share liability unhelpful, as unlikely to be applied. A less stringent requirement might incentivize operators to lose their spacecraft intentionally. Also, it appears clear that collisions involving identifiable objects would still be subject to the Liability Convention's weak fault-based liability.

Using the theory of market-share liability in the space debris context would require ratification of a new treaty or amending the Liability Convention (see Sundahl, 2000, for a draft of a potential amendment), as states would need to agree on this new apportionment of liability between them. Disputes over the correct market shares calculation may arise, and the introduction of a new expense is unlikely to please the large contributors to the space debris population (Muñoz-Patchen, 2018). However, countries that would be paying the highest cost—the US, Russia, and China—are also the ones with the highest risk exposure. As orbital debris is threatening their space activities, they might welcome this mechanism as it shares the costs according to each state's contribution to the problem and avoids the free-rider problem (Muñoz-Patchen, 2018). Market-share liability in the orbital debris context would require buy-in from at least a majority of spacefaring nations. The mechanism could work without all spacefaring states taking part,[26] but this would drastically reduce its risk-reducing ability.

The market-share liability doctrine would offer a way of apportioning liability between states for damage caused by unidentifiable debris. Thus, states would have an incentive to mitigate debris creation and remove existing debris (see, e.g., Limperis, 1998; Sundahl, 2000). This argument relies on the use of a proportional liability based on the share of identifiable debris (identifiable market-shares). In this case, states have an incentive to reduce the generation of and remove large debris as it would reduce their liability exposure. However, there is a potential loophole in the identifiable market-shares method. If states can blow up their spacecraft in a way that results only in unidentifiable debris, they could reduce their liability exposure. This point highlights that the identifiable market-shares method is an imperfect proxy of the risk caused by unidentifiable debris. Using modeled market shares instead, removing or creating identifiable debris will not

[26] Non-participating states would not be compensated. Each state would be liable for its respective share, but the compensation would be incomplete.

directly affect the shares. In the case of removal, it only prevents the share from growing, as the removed object might have produced unidentifiable debris through explosion or collision.

M. W. Taylor (2007) notes that the orbital debris context is significantly different from the one addressed in *Sindell*. In the space law regime, all rights and responsibilities flow through states, making them both claimants and respondents. A full recovery would not be possible, as a claimant state's damages will always be offset by the proportion of debris for which it is responsible. M. W. Taylor (2007) argues that this proposal is skewed in favor of states which have produced a relatively small amount of debris. This observation reinforces the idea that finding agreement between spacefaring nations on such a proposal might be unreachable. Moreover, apportioning liability among spacefaring nations is not a sufficient mechanism to mitigate and reduce space debris, as the actors performing the activity, i.e., the operators, are not the bearers of this liability. There is still a need for a national mechanism to reduce a nation's liability exposure, either by a transfer of liability or any other mechanism. Other advantages and disadvantages of the market-share liability doctrine applied in the space debris context are discussed in Sundahl (2000, p. 147–152).

6.4.2 Market-share disposal payments

Market-share liability can be useful to provide compensation to the victims of collisions (if an appropriate trigger can be found) and to incentivize debris mitigation (to some degree, depending on the shares calculation method). However, it is not sufficient to remedy the persistent existence of space debris. Muñoz-Patchen (2018) argues that "states should be required to pay for the disposal of debris in proportion to the amount they create." She argues that the market-share liability framework could offer the basis for an UN-managed fund that would provide reimbursement payment to states undertaking retrieval activities.[27] Nations or companies would be compensated for the cost of their clean up activities through market-share payments. The apportionment of liability would be done on an ongoing or periodic basis to reflect new developments.

Muñoz-Patchen (2018) does not offer more details on the implementation of the market-share disposal payments, but they could work similarly to the bounty payments proposed by Carroll (2019, see § 6.2.2 and § 6.2.3). The major difference

[27] Muñoz-Patchen (2018) circumvent the problem of the strong property ownership regime of the space treaties by combining the current definition of space debris and the doctrine of abandonment.

between these two proposals is not how the money is allocated but the generation mechanism. In Carroll's proposal, the money is generated through a form of regulatory fee and thus is imposed only on the actors using space once the policy is enacted. The market-share liability payment requires all actors that have contributed to the current level of debris-related risk to contribute. I extend the discussion about burden-sharing between current and past space actors in § 7.1. Muñoz-Patchen is able to devise a mechanism that makes past space actors pay for the risk they have created because she relies on the national conception of space activities embedded in the UN treaties. This proposal would thus require international cooperation. I extend the discussion on the feasibility of applying market-based approaches at different jurisdictional levels in § 7.2.

7 A dichotomy of debris-related risks

7.1 Reducing risks from historic and new debris

For policy purposes, we can distinguish two sources of debris-related risks: the historic and new debris populations. All non-functional human-made objects currently in space form the population of historical debris. In contrast, the new debris population does not yet exist and will be created by all space activities conducted in the future. The boundary between those two populations is set to the moment a new policy to curb space debris is enacted, separating debris created prior to the policy enactment to the ones not yet created at that moment. For simplicity, I assume in the following discussion that such policy emerges now.

Although irrelevant from a risk perspective, the distinction between these two populations is crucial when assigning responsibilities and addressing burden-sharing. While actors of the past have conducted activities that have created the current level of debris-related risk, any new activity will add some incremental debris-related risk. As actors responsible for those two populations of debris are not the same, a single policy approach is unlikely to be politically feasible. Furthermore, it is technically and politically easier to reduce the risks not yet created. For example, ex-ante measures are no longer a viable option to lessen the risk caused by historical debris.

Although much of the attention has been focused on the incremental risk caused by the planned increase in new launches (e.g., Le May et al., 2018; Radtke et al., 2017; Somma et al., 2019), clusters of derelict objects abandoned in some altitude bands in LEO could cause a greater threat of collision (e.g., McKnight et al., 2019; Rossi et al., 2019).

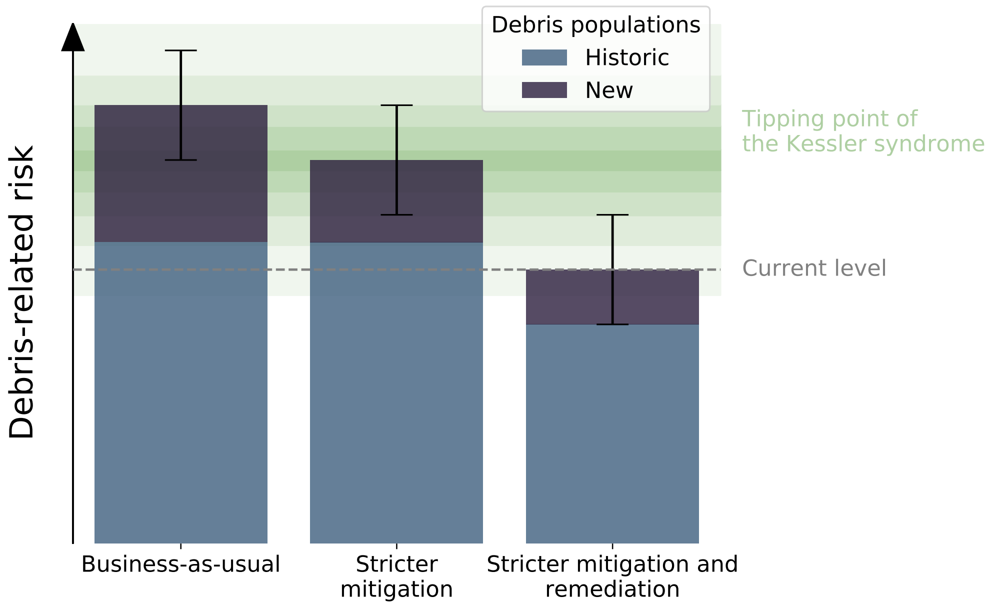

FIGURE 7.1 – Schematic representation of future debris-related risk under three policy scenarios.

Note: Levels and uncertainties are arbitrary and only illustrative of the relative effect of the three policy scenarios. The level and Gaussian uncertainty on the tipping point of the Kessler syndrome are set arbitrarily.

Reducing the cost of historical and new debris calls for different actions. For historical debris, it is too late to prevent their creation; only remediation is feasible. In contrast, we can still prevent the creation of new debris (i.e., ex-ante mitigation is possible). For new space activities, we can internalize the cost of space debris creation, such that this cost is taken into account when taking decisions.

The command-and-control approaches I have explored in chapter 5 are aimed solely at dealing with the new debris problem. It creates standards to limit the augmentation of debris-related risk but does not attempt to reduce the debris-related risk due to historic debris. The market-based approaches presented in this chapter are also aimed at reducing the incremental debris-related risk of new activities. However, some of them can, at the same time, reduce the threat of historical debris. When the mechanism generates money, it provides the resources necessary to conduct remediation activities to lessen the threat of historical space debris.

Figure 7.1 depicts schematically the evolution of the debris-related risk under different policy scenarios. Under a business-as-usual scenario, the debris-related risk will grow by an uncertain amount. With stricter mitigation measures, the debris-related risk will also grow by an uncertain amount, but smaller, as stricter mitigation measures reduce the creation of new debris. For both scenarios, the debris-related risk due to historic debris will grow of about the same amount.[1] If remediation measures are added on top of the stricter mitigation measures, both the historic and new debris-related risk can be reduced.[2] There is not only uncertainty in the effect of the policy measures, but also on the level of the debris-related risk which is the tipping point of the Kessler syndrome.

There is growing agreement in the space community that mitigation measures will not be sufficient to keep the space environment sustainable (e.g., Lewis et al., 2012; Liou & Johnson, 2006, 2008; Liou et al., 2010). Remediation will require the active retrieval of space objects which is costly (see § 3.3.4). The ability of a policy approach to create at the same time incentives for ex-ante mitigation and generate money to fund remediation measures is a significant advantage. Two of the approaches discussed in this chapter achieve these combined goals: a cap-and-trade scheme with auctioned allowances and regulatory fees. If the insurance market acts as a surrogate regulation and collision risk increases too much, insurers could theoretically use some of the money earned through premiums to purchase active retrieval services to decrease the risk. However, such an outcome seems unlikely. More probable is insurers unwilling to provide coverage. Finally, in the case of market-share liability, both identifiable and modeled market-shares provide incentives (though weak) to take mitigation and remediation measures. Market-share disposal payments are a direct mechanism to fund remediation.

Actors responsible for the current level of debris-related risk are of two types: states and private companies. States conducted both civil and military space missions, while private companies have conducted commercial activities. Most of the current debris-related risk is due to state activities and not private ones, but the future debris-related risk will be mainly created by private companies. The legal regime governing space is centered on states which bear "international responsibility for national activities in outer space, [...] whether such activities are carried on by governmental agencies or by non-governmental entities" (Outer Space Treaty, 1966, Article VI). Given those two observations, reducing the historic debris-related risk should probably rely on a state-centric approach. That is precisely what the market-share disposal payments scheme does, requiring actors of the past to pay for the remediation of the debris-related risk they have created.

[1] "Even without new launches, collisions will continue to occur in the LEO environment over the next 200 years, [...] and will force the debris population to increase" (Liou & Johnson, 2006). Note that the historic debris-related risk will potentially grow more in the business-as-usual scenario because the interaction between the historic and new debris population will produce more collisions due to the higher new debris-related risk.

[2] Derelict objects from both the historic and new debris population can be removed from orbit.

Contrary to market-share disposal payments, regulatory fees and cap-and-trade results in future space actors funding remediation of the historic debris-related risk. Future private actors might be unwilling to fund this remediation, which would hamper the political feasibility of those regulatory approaches. Thus, two different mechanisms might be required, one to remediate the historic debris-related risk and one to both mitigate and remediate the future debris-related risk. For the former, it seems that a form of international agreement might be necessary, while for the latter, this might not be the case. I further the discussion on the jurisdictional level of the regulation in the next section.

7.2 Policy approaches at varying jurisdictional levels

Can the policy approaches detailed in chapter 6 be applied at the national level, or do they require some form of international cooperation? Most authors have developed those regulatory approaches with the idea that a comprehensive binding regulatory regime would be required (e.g., Muñoz-Patchen, 2018; Pecujlic & Germann, 2015; Roberts, 1992), but this might not be the case. I follow the dichotomy presented in the preceding section between historic and new debris-related risks and discuss the jurisdictional level feasible to address both risks with different policy approaches.

7.2.1 Approaches to the historic debris-related risk

The reduction of the historic debris-related risk requires some form of international cooperation. A state cannot fully internalize the benefits of taking remediation measures (e.g., ADR), as other states will benefit from its risk-reducing activities. Thus states will, in the best-case scenario, underfund remediation, and in the more likely scenario, not fund it at all. Without an agreement, some states will likely free-ride on the efforts of the others. To prevent this from happening, cooperation between states is required. Responsibility for the current level of debris-related risk is not evenly shared among spacefaring nations. Three states are responsible for the majority of the debris-related risk: Russia owns 66.5%, the US 12.5%, and China 10.5% of the mass in LEO (data as of April 2016, Carroll, 2019; see also McKnight et al., 2019). Only one of the approaches discussed addresses the apportionment of liability and remediation costs for the historic debris-related risk: market-share liability and market-share disposal payments. This approach requires an international agreement between (at least a majority of) the nations responsible for the current debris population. Muñoz-Patchen (2018) argues that although states would not be pleased by the newly found expense, this scheme could be feasible as states responsible for space debris are also those with the highest interest in preserving space. However, this argument does not survive the analysis of international talks on the matter in the past thirty years. Although there have been numerous calls for a new binding international regulatory instrument (e.g., Ellery, 2019; Imburgia, 2011; Roberts, 1992; Sénéchal, 2007), there has been almost no progress in this direction. The last product of the international community regarding space governance, the Moon Agreement (1979), is more than five decades old and has been ratified by none of the major spacefaring nations. Despite numerous loopholes in the UN treaties governing space, there has been no attempt at reforming the legal framework. Reasons for this status quo are numerous and include, e.g., multipolar international relations and space weaponization (see Shackelford, 2014, for a discussion of the factors paralyzing the development of the space law regime and how polycentric networks could help manage the collective action problem). Obstacles to a new international binding regulatory regime could theoretically be overcome, but most observers agree that an international treaty is unlikely to emerge in the near future (e.g., Imburgia, 2011; Sénéchal, 2007).

A differing point of view is offered by Kurt (2015), who believes that "the space debris problem can be effectively addressed without a binding treaty." He argues that the economic assumption regarding common resource problems should be revised. Building on the works of Ellickson (1991) and E. Ostrom (2009), he argues that voluntary cooperation between spacefaring nations on the issue of space debris "is common sense." To support his optimism that the tragedy of the commons can be avoided, he takes efforts to mitigate climate change as a model of cooperation and takes the example of voluntary efforts led by the US and Brazil. The US withdrawal from the Paris agreement and President Bolsonaro's policies aimed at reducing Brazil's efforts to mitigate climate change question Kurt's conclusions.

Carroll (2019) observes that the US has more invested in LEO than any other country and that this trend might even increase in the near future with the advent of megaconstellations. Thus, the US has a substantial interest in preserving a sustainable space environment. At the same time, about two-thirds of the mass in LEO is owned by Russia. Thus, Carroll (2019) argues that LEO debris is primarily a US-Russia bilateral issue. Although political tensions between Russia and the US are at their highest since the cold war, even in the space domain (Erwin, 2020b), cooperation could be beneficial to both space actors. Anzaldua and Dunlop (2015) argue that both spacefaring nations share an interest in and responsibility for ensuring a safe and sustainable space environment. They argue that the derelict Russian objects have a sizeable potential value if they can be re-purposed or recycled in-orbit. Along this line is a comment made at an April 2010 debris meeting in Moscow by Dr. Valentin Nataluha of the Russian Foreign Ministry suggesting to a colleague that de-orbiting rocket bodies was a loss of valuable material, and that recycling in orbit is preferable (reported by Carroll, 2019). This suggests that Russia might be willing to sell its debris. Although the technology for in-orbit recycling is not yet available, Anzaldua and Dunlop (2015) argue that the US should already engage in talks with Russia. They bring two other arguments that could encourage Russia to cooperate: First, albeit weak, Russia bears some liability risk for its derelict objects. Second, cooperation with the US could help Russia advance its space technology and industry. They also note that, as states are particularly sensitive regarding their satellite capabilities, retrieval should first be focused on rocket upper stages, which are less sensitive and make about half of the LEO debris mass.

The feasibility of bilateral cooperation is put into question by the increased Chinese and Indian activities in LEO. McKnight et al. (2019) observe that China is responsible for 41% of the total number of rocket bodies abandoned over the last five years, and that out of the 16 launches conducted by India above 650 km in LEO, eight rocket bodies have been left. The growing contribution of China and India to the large derelict population in LEO questions the feasibility of a US-Russia bilateral approach and makes the potential negotiations between these four actors more complex.

7.2.2 Approaches to the new debris-related risk

When it comes to mitigating or remediating the incremental debris-related risk posed by the future space activities, the majority of authors have relied (sometimes implicitly) on a binding international agreement to enforce their market-based approach proposals. The cap-and-trade mechanism proposed by Pecujlic and Germann (2015) relies on drafting an international treaty, or on amending the Kyoto Protocol or the Paris Agreement to extend their scope to include space environment protection. Orbital tax proposals (e.g., Akers, 2012; Pusey, 2010) are also envisioned at the international level. Akers (2012) argues that a regulatory fee addressing the future debris-related risk is more feasible than assigning liability for the current level of debris-related risk. Rather than apportioning responsibility for past activities, focusing on the future clean up of orbital debris might help states cooperate.

J. B. Taylor (2011) observes that "[t]reaties bind only those who consent to be bound" (citing Wiener, 1999). Thus a policy addressing space debris must be

Pareto-improving to be adopted at the international level. He argues that, although regulatory fees and marketable permits are "equally superior to conduct-based regulatory strategies" on cost-efficiency grounds and innovation-generation potential,[3] marketable permits are preferable when "participation-efficiency" is taken into account. His argument goes as follows: Both market-based approaches impose costs on space debris sources. Only states for which the benefits of cleaner orbits outweigh the costs of taking part would sign a treaty. States for which the abatement costs are greater than the benefits would not take part without compensation. Thus any treaty would require side-payments from the net beneficiaries to the net losers.[4] Those side-payments undermine the efficacy of a regulatory fee scheme as states receiving the side-payments are no longer incentivized to reduce their debris generation. If the cost of the regulatory fee is reimbursed through a side payment, generating debris becomes costless compared with abatement. The marketable permit scheme is not subject to this problem as it caps the total level of debris-related risk that can be created. Under such a scheme, the side-payments would take the form of extra permits in the initial allocation. To secure the net losers' participation, they would be granted extra permits.[5] Side payments occur on an ongoing basis under the regulatory fee scheme while they are fixed at the initial allocation in a marketable permit scheme. This discussion highlights that the permits allocation mechanism is of prime importance to secure wide participation and make the application of such a scheme at the international level feasible.

Although I have pointed out some pathways to ease international cooperation, we have seen in the preceding section that the emergence of a binding international instrument is highly unlikely. So, could the market-based approaches described in this chapter be applied at the national level? Space commons can be accessed from anywhere on the planet, and space debris is truly a global problem. No single nation is responsible for the current level of debris-related risk, and a larger number of them will likely be responsible for the incremental debris-related risk that will be created by future space activities. Thus, unilateral action by a nation or a group of nations would be less efficient than international cooperation. However, given the enormous obstacles towards international regulation, the higher political feasibility of national regulation could make it the jurisdictional level of choice. Such national regulation could be embedded in a state's national space law or in the licensing

[3] As we have seen in § 6.1 and § 6.2, this claim holds only under certain particular conditions. Regulatory fee can be superior, on cost-efficiency grounds and innovation-generation potential, to marketable permits and vice versa depending on the implementation, the "market" conditions, and the information available to the regulator.

[4] The policy itself no-longer needs to be Pareto-improving. A Kaldor-Hicks improvement with side-payments is sufficient (leading to a Pareto improvement overall).

[5] Net losers could sell those permits, thus creating a side-payment, or keep them to create the associated debris-related risk through their space activities.

requirements for launchers and spacecraft operators.

In this regard, GHG emissions share several similarities with space debris. GHG diffuses uniformly across the atmosphere, and emission reduction by one country benefits all countries, thus leaving the risk of a "free rider" problem if countries pursue their self-interest (Barker & Crawford-Brown, 2015). The international community has been only partially successful in coordinating global action to reduce GHG emissions. Although the Kyoto Protocol (1997, Article 17) provides for an emission trading scheme between state parties, such a regulatory instrument has been commonly adopted at the national or even regional level. As of 2019, 28 emission trading systems were established in regional, national, and subnational jurisdictions. Similarly, 29 carbon taxes were in place primarily at the national level (World Bank, 2019). The existence of market-based instruments at the national level to curb GHG emissions shows that the use of such instruments in the space debris context could be feasible.

The primary concern with unilateral action is the potential reduction in international competitiveness of the industry regulated and the relocation of the regulated activity to other countries (Barker & Crawford-Brown, 2015). This effect, known as "carbon leakage" in the case of policies aimed at reducing GHG emissions, reduces the policy's effectiveness and creates an excess burden for the regulating country to the extent that relocation reduces output, employment, and taxable profits at home (R. Martin, Muûls, et al., 2014). These concerns have often been the principal argument against the establishment of carbon pricing mechanisms. To prevent carbon leakage, almost all of the carbon taxes that emerged in Europe in the past decades have included rebates or exemptions to energy-intensive firms. The European Union Emissions Trading Scheme (EU ETS), the largest multinational GHG cap-and-trade scheme of the world, exempts industries deemed at risk of carbon leakage from permit auctions (Juergens et al., 2013; R. Martin, Muûls, et al., 2014). The methodology used to grant exemptions has been criticized as "more politically driven than economically grounded" (Clò, 2010, p. 2420). Different options are available to the regulator to prevent leakage—a border charge on imports, a border rebate for exports, full border adjustment, and domestic output-based rebating—but Fischer and Fox (2012) show that those options cannot be ranked as their effectiveness depends on the relative emission rates, elasticities of substitution, and consumption volumes. While mechanisms have been devised to minimize the effect of carbon leakage (e.g., Sun et al., 2019), the evidence for the existence of this effect is mixed. In analyzing the impact of a carbon tax on manufacturing plants using panel data from the UK production census, R. Martin, de Preux, et al. (2014) show no evidence of adverse impacts on employment, revenue, or plant exit. The empirical literature on the EU ETS shows that there have been hardly any effects on firms' competitiveness or profitability (see Joltreau & Sommerfeld, 2019, for a review). However, Joltreau and Sommerfeld (2019) trace the absence of a negative effect on firms' competitiveness to the large share of permits allocated for free, the over-allocation of emission permits, and the firms' ability to pass on the permit costs to customers. The fear that regulation might drive business abroad is not the sole result of market-based approaches. Unilateral command-and-control regulation faces the same issue (see Dechezleprêtre & Sato, 2017, for a review of the empirical literature on the impacts of environmental regulations on firms' competitiveness).

Would unilateral action in the space debris context lead to "debris leakage"? While some authors express this concern (e.g., Garber, 2017), there has been no investigation of the relevance of this effect in the space debris context. Assessment of the ability and willingness of space actors to shift their license application to other jurisdictions should be conducted. Whereas most activities emitting GHG can be carried out anywhere on the planet, only a limited number of states have launch capabilities. Furthermore, some commercial space activities, such as telecommunications, often require market access through a regulatory process (e.g., the FCC grants market access in the US). The latter can be used to limit the risk of debris leakage. Let us assume that country C enacts a policy (command-and-control or market-based) to curb the creation of space debris. If C applies similar requirements for market access and licensing, relocation of activities in foreign countries F will be reduced. This approach only works if C is a sufficiently large market without which commercial activities would be significantly less profitable. Otherwise, satellite operators would shift licensing to F and decide not to serve C. Although this approach is easier to implement for a command-and-control approach, it could be implemented for market-based approaches. If an operator licensed in F is not subject to a market-based mechanism aimed at reducing debris generation, accessing the market in C would require the operator to be part of the market-based mechanism. It could thus be required, e.g., to hold third-party liability insurance, pay regulatory fees when creating debris, or hold marketable permits matching the debris created. The US is well placed to enact such unilateral regulation as its market is large, and the FCC already requires foreign-licensed operators seeking market access to abide by its space debris rules (see § 5.4.4). Currently, this requirement can be waived if the operator shows that it is subject to effective regulatory oversight by the satellite system's national licensing authority. To prevent "debris leakage", such a waiver should not be available to operators seeking market access.

8 Conclusion

In this work, I compared the different policy approaches available to the regulator to contain the growth of debris-related risks. By analyzing an ongoing US reform of orbital debris mitigation rules for commercial satellites, and the stakeholders' position vis-à-vis this reform, I have highlighted the limits of the command-and-control approach focused on ex-ante requirements. Recognizing that at the source of the problem is a lack of incentive for space operators to reduce their debris creation and to remove derelict objects points to the use of market-based instruments. I detailed and compared four policy instruments based on the market that could be applied in the space debris context: marketable permits, regulatory fees, liability insurance, and market-share liability and disposal payments.

The analysis of space debris revealed that the issue has two facets, which call for different policy responses. First, the current debris-related risk results from past space activities and cannot be reduced by changing the actors' behavior. Reducing this risk requires remediation and a mechanism to allocate its costs. Dealing with the historic debris population should probably rely on a state-centric approach, in the form of an international agreement to avoid free riding. The market share-disposal payments, which consist of apportioning the remediation costs proportionally with a state's current debris population, appear as an efficient approach. However, the funding of clean up activities by governments in democratic societies is dependent on the perception by the general public of the matter (see Appendix F regarding public opinion on space debris).

Second, the future debris-related risk, which will be the result of space activities to come, calls for a very different approach. In this case, the regulatory instrument must be able to incentivize actors to reduce their debris generation. The command-and-control approach results in uniform requirements and is thus inefficient as space actors have varying abatement costs. Moreover, it fails to align operators' incentives and space sustainability goals.

Relying on the liability insurance market to incentivize risk-reducing behaviors requires only limited intervention from the regulator. However, the conditions for a well functioning liability market are not present: the international liability framework for in-orbit activities is weak, and the remote nature of space prevents damage investigation. Marketable permits and regulatory fees thus appear as the preferred instruments as they both efficiently internalize space debris costs. Both require the design of an appropriate unit of risk that drives permit requirement or fee liability. I have proposed a fungible unit of debris-related risk, which prevents leakage of the externality. A marketable permit scheme with a cap on debris creation is probably the most effective mechanism as it would limit the number of new debris created to a fixed amount, but the design of such a scheme is complex. Regulatory fees might be preferred as they offer more certainty on the cost of abatement and motivate long-term investments in mitigation.

Recently, the FCC proposed the introduction of a post-mission disposal bond, which is a kind of regulatory fee. Deposit and refund schemes would incentivize operators to reduce unplanned debris creation and post-mission disposal. However, requiring a sizeable ex-ante payment could be an obstacle to innovation and new space applications. To alleviate this issue, I proposed to couple a deposit and refund scheme with a periodic fee.

An argument against the enactment of more stringent rules regarding space debris mitigation unilaterally is that it will encourage forum shopping and lead to debris-related risk leaking from the jurisdiction with higher requirements to jurisdictions with lower ones. Although multilateral action would entirely prevent leakage, mechanisms exist to enact rules locally and alleviate leakage concerns. I argued that unilateral action from the US could be effective as the same requirements can be applied to entities requiring US market access. This mechanism can prevent operators from seeking to license in countries with less stringent regulation and could help drive change abroad.

Evaluating policy approaches requires data on their costs and benefits. In the space debris context, this data is largely lacking. The current economic impact of space debris is unknown, while the future economic impact is hard to predict. There are three main reasons for the current cost data scarcity issue. First, damages due to untracked debris are unreported. The development of new technologies to monitor on-orbit satellite damage due to space debris could help evaluate those costs (e.g., Englert et al., 2014). Second, satellite operators are not transparent regarding the costs they face, e.g., for shielding, collision avoidance maneuvers, and post-mission disposal. Third, spending in Space Situational Awareness not only benefits space debris mitigation but also has military purposes. The recent availability of the first end-to-end (i.e., from radar observations to data analytics) commercial collision avoidance services could provide insights into those costs (e.g., Shouppe, 2020; Werner, 2020).

Data on the future economic impact of space debris and the economic impact of mitigation and remediation is even scarcer. The global nature of near-Earth orbital space and the long timescale on which actions affect the space debris population prevent any empirical policy evaluation. Contrary to other domains, the impacts of policies can only be evaluated through modeling, which requires strong assumptions. Not only future activities in space and the effect of mitigation and remediation are uncertain, but the total economic value of near-Earth orbital space is elusive. However, there is no doubt that without action, the costs of space debris in the near future will be daunting. The limited data available prevents a comprehensive cost-benefit analysis but should not be a reason to postpone action. Maximizing social welfare and the benefits we derive from space require addressing the root causes of space debris creation. Instruments presented in this work can induce the reduction of debris generation and realign space operators' incentives with sustainability goals.

A Planned satellite constellations

The list of planed satellite constellations used in Figure 2.3 is presented in Table A.1. For similar listings, see, e.g., Muelhaupt et al. (2019, Table 1), or NewSpace Index (2020).

Table A.1 – Planned satellite constellations.

Operator/ Owner	Name	Country of Operator/ Owner	N_{Sat}	Altitude [km]
Amazon	Kuiper System 1	US	1156	630
	Kuiper System 2		1296	610
	Kuiper System 3		784	590
OneWeb	OneWeb 1	UK	648	1200
	OneWeb 2		1332	1200
SpaceX	Starlink Phase A	US	1584	550
	Starlink Phase B1		1600	1110
	Starlink Phase B2		400	1130
	Starlink Phase B3		375	1275
	Starlink Phase B4		450	1325
	Starlink VLEO 1		2547	346
	Starlink VLEO 2		2478	341
	Starlink VLEO 3		2493	336
Telesat	Telesat LEO 1	Canada	60	1000
	Telesat LEO 2		45	1248
Theia Holdings	Theia Satellite Network	US	120	800
Kepler Communication	Kepler Communication	Canada	140	600
CASIC	Hongyun	China	156	1100
GalaxySpace	GalaxySpace	China	144	637
CASC	Hongyan	China	320	1100
Northstar Earth & Space	Northstar Earth & Space	Canada	40	550

B Common-pool resources: Solving the management problem

B.1 What is a common-pool resource?

Following the work of Buchanan (1965), V. Ostrom and Ostrom (1977), and Samuelson (1954), economists classify goods depending on two characteristics: excludability and rivalry (or subtractability of use). A good is excludable if people can be prevented from using it when they do not pay for it. It is rival if an individual's use diminishes other people's use. These two characteristics are continuous and can range from low to high. Using these two characteristics, goods can be grouped into four broad types—private goods, toll goods, common-pool resources, and public goods—which are summarized in Table B.1. Producing, providing, managing, and consuming these different types of goods require different institutions. The problem faced in devising them is often specific to each category of good. In each of those four types of goods, there exist subtypes that vary substantially in many attributes (E. Ostrom, 2010).

A common-pool resource (CPR) is a subtractable natural or human-made resource system faced with an open-access problem. The issue stems from two of its characteristics: it is "sufficiently large as to make it costly (but not impossible) to exclude potential beneficiaries from obtaining benefits from its use" (E. Ostrom, 2015) and its use by one actor subtracts the ability of another actor to use the same resource. Those two characteristics—the subtractability of the resource units and the jointness of the resource system—must be distinguished to avoid the common confusion between CPRs and public goods. For CPRs, physically excluding users from accessing the resource or improvements made to the resource system is relatively costly. Similarly, excluding potential beneficiaries from public goods is costly (E. Ostrom, 2015). The high cost in excluding beneficiaries results

Table B.1 – Goods classification in four types (adapted from E. Ostrom, 2010).

		Difficulty of excluding potential beneficiaries: Low	Difficulty of excluding potential beneficiaries: High
Subtractability of use	Low	*Toll goods* E.g., cinemas, private parks, cable TV, uncongested toll roads	*Private goods* E.g., food, clothing, cars, parking spaces, congested toll roads
	High	*Public goods* E.g., free-to-air radio, air, national defense, uncongested non-toll roads	*Common-pool resources* E.g., fish stocks, timber, coal, congested non-toll roads

in the same temptation to free-ride for CPRs and public goods. However, the use of a public good does not subtract from the availability of this good to others. Someone's consumption of, e.g., free-to-air radio, weather forecasts, or national security, does not affect the level of availability of these public goods to others. Contrary to public goods, the subtractability characteristics of CPRs can lead to the overuse of the resource, leading to its degradation, congestion, or even destruction. Resource systems (e.g., lake, bridge) must be distinguished from the flow of resource units harvested (e.g., number of bridge crossing per year, tons of fish harvested). The distinction is especially important for renewable resources for which a replenishment rate can be defined. Under favorable conditions, a maximum flow of resource units can be harvested without harming the stock or the resource system (E. Ostrom, 2015). CPRs can be differentiated due to (1) their provision, (2) their physical characteristics, (3) their types of use, and (4) their ownership (E. Ostrom, 2003; E. Ostrom & Gardner, 1993). Firstly, CPRs can be human-made (e.g., roads) or provided by nature (e.g., forests). Secondly, they can be renewable (e.g., fish stocks) or non-renewable (e.g., minerals), stationary (e.g., lake) or non-stationary (e.g., migratory fish), symmetric (e.g., lake) or asymmetric (e.g., irrigation system). Renewable CPRs naturally replenish. To sustain their availability, the average rate of withdrawal must not exceed the average rate of replenishment. The asymmetrical property denotes the differential ease of access to the resource among actors. Thirdly, CPRs can be used locally (e.g., bridge) or globally (e.g., internet). Moreover, CPRs can be used as a mean or as an end. Actors can derive an indirect advantage from a CPR (e.g., carbon storage in the atmosphere) or a direct advantage (e.g., fish consumption). Fourthly, CPRs can be owned by a wide variety of actors: national, regional, or local governments, communal groups, private individuals, corporations, or nobody. Hence, CPRs exist under a wide variety of property rights.

‘Global commons’ is a more general concept that describes resource domains extending beyond national boundaries and containing CPRs. The high seas, the atmosphere, Antarctica, and outer space are traditionally categorized as global commons (see, Hertzfeld et al., 2015, for a discussion on the legal and historical classification of outer space). Global commons often encompass CPRs of different types. For oceans, the focus of CPRs studies has been on fisheries, but other oceanic resources, such as marine biodiversity or carbon storage, are CPRs (Rickels et al., 2016).

B.2 The tragedy of the commons

Due to their open access and subtractability of use, CPRs face a management problem. Self-interested individuals use the resource as long as their private marginal benefits exceed their marginal costs. Individuals’ failure to integrate the costs they impose on other users of the resource leads to its over-exploitation. Since Hardin (1968), this problem has been referred to as “the tragedy of the commons.” Although Hardin popularized this concept, its awareness dates back as far as Aristotle (see E. Ostrom, 2015, chapter 1, for a short review of the literature on the tragedy of the commons predating Hardin’s influential paper). Hardin (1968, p. 1244) used the metaphor of a common grassland to depict the tragedy:

> Picture a pasture open to all. It is to be expected that each herdsman will try to keep as many cattle as possible on the commons. [...] As a rational being, each herdsman seeks to maximize his gain. Explicitly or implicitly, [...] he asks, “What is the utility to me of adding one more animal to my herd?” This utility has one negative and one positive component. [...] Since the herdsman receives all the proceeds from the sale of [one] additional animal, the positive utility is nearly +1. [... H]owever, the effects of overgrazing are shared by all the herdsmen, the negative utility for any particular decision-making herdsman is only a fraction of −1. The rational herdsman concludes that the only sensible course for him to pursue is to add another animal to his herd. And another; and another... But this is the conclusion reached by each and every rational herdsman sharing a commons. Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit—in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all.

TABLE B.2 – Payoff matrix of a prisoner's dilemma game.

		Herder 1			
		Cooperate		Defect	
Herder 2	Cooperate	10	10	-1	11
	Defect	11	-1	0	0

The tragedy of the commons depicted by Hardin is often formalized using games theory as a prisoner's dilemma (PD) game (e.g., Dawes, 1973, 1975). The PD is an archetypal game which, in the case of Hardin's pasture example, takes the following form: Two herders use a common grazing meadow which can only feed S sheep on its grounds. Each herder can decide to "cooperate" and have $S/2$ sheep on the meadow. However, each herder could increase its profit by having more than $S/2$ sheep. If one herder decides to "defect" (i.e., have more than $S/2$ sheep), he obtains 11 units of profit while the other herder gets the "sucker's" payoff, -1. If both herders decide to defect, they both get zero profit. The payoff matrix of this game is shown in Table B.2. This conceptualization of Hardin's tragedy of the commons is a noncooperative game in which all players possess complete information. Communication among the players is either not possible or not relevant as agreements are non-binding (E. Ostrom, 2015). In the PD game, the "defect" strategy is dominant[1] for both players. The equilibrium resulting from each player choosing their "best" individual strategy result in a Pareto-inferior outcome, as both players would prefer the outcome when they both cooperate. Although based on strong assumptions, the PD suggests that rational individuals are unable to cooperate. Such a puzzling outcome has given rise to a large body of work. The observation that "individually rational strategies lead to collectively irrational outcomes seems to challenge a fundamental faith that rational human beings can achieve rational results" (E. Ostrom, 2015, p. 5).

In addition to the tragedy of the commons and the prisoner's dilemma, a third model tries to explain the difficulties in reaching a Pareto optimal outcome in collective decisions. In his book "The Logic of Collective Actions", Olson (1965) challenges the idea that self-interested individuals who have a common interest would act to further that interest. Olson argues that the possibility of obtaining some benefits from cooperation is not sufficient to generate the necessary collective action to achieve that benefit. He argues that "unless the number of individuals is quite small, or unless there is coercion or some other special device to make individuals act in their common interest, rational, self-interested individuals will not act to achieve their common or group interests" (Olson, 1965, p. 2). The

[1] A dominant strategy provides greater utility to a player, independently of the other player's strategy.

rational sustaining this claim is that if individuals cannot be excluded from the benefits of the collective good or action, they do not have an incentive to voluntarily contribute to that good or action.

The three models explored—the tragedy of the commons, the prisoner's dilemma, and the logic of collective action—all depict the same situation where individuals are tempted to free-ride on the efforts of the others. As long as individuals cannot be excluded from the benefits provided by others, they have an incentive to avoid contributing, resulting in an underprovision of the collective benefit (E. Ostrom, 2015).

B.3 Managing common-pool resources

Hardin (1968) and others before him propose two institutional solutions to the tragedy of the commons: private property rights or government control. Correcting the inefficiencies that result from the non-excludability of the resource can be solved by establishing property rights, thus eliminating the common access (Coase, 1960; Demsetz, 1967). Developing private property rights in case of stationary CPRs such as a meadow requires dividing the land into separate parcels. When this approach is used for non-stationary CPRs (e.g., water or fisheries), its implementation is far more difficult. In this case, a wide variety of rights can be established: rights to use the resource system at a particular place and time, rights to withdraw a particular amount of resource units, or rights to use particular equipment or technologies. However, this approach does not result in private ownership of the resource system itself (E. Ostrom, 2015). The second approach sees the centralized control of governments over CPRs as the solution to the tragedy of the commons. For example, Ophuls (1973, p. 228–229) argues that "because of the tragedy of the commons, environmental problems cannot be solved through co-operation [...] and the rationale for government with major coercive powers is overwhelming" and concludes that "even if we avoid the tragedy of the commons, it will only be by recourse to the tragic necessity of Leviathan." These two solutions to the management of CPRs are not always the panacea and are extrema on the spectrum of institutional solutions available. E. Ostrom (2015) and her colleagues extensively studied CPRs management both in laboratory experiments and field research. In the laboratory setting, they showed that individuals exhibited more complex patterns of decisions (e.g., the use of reciprocity to overcome social dilemmas) than previously assumed by proponents of the two extremal solutions to CPRs management. Through field research, they uncovered many institutional forms devised by communities to manage the specific features of their CPR. This body of work highlighted many examples of successful management of CPRs without the use of private property or government control (e.g., Lam, 1998), and some unsuccessful outcomes where those two management methods have been used (e.g., Sneath, 1998). By examining the diversity of institutional arrangements leading to successfully managed CPRs, E. Ostrom (2015, p. 90) noticed the presence of eight essential elements or conditions that helps to account for the success of these institutions (see Cox et al., 2010, for an analysis of the relevance of the design principles for community-based CPR management through a review of more than 100 studies). These eight "speculative design principles" (or "best practices") are:

1. *Clearly defined boundaries:* Boundaries and rights to withdraw resource units from the CPR must be clearly defined;

2. *Congruence between appropriation and provision rules and local conditions:* Appropriation rules restricting time, place, technology, and/or quantity of resource units are related to local conditions and to provision rules requiring labor, material, and/or money;

3. *Collective-choice arrangements:* Most individuals affected by the operational rules can participate in modifying the operational rules;

4. *Monitoring:* Monitors, who actively audit CPR conditions and appropriator behavior, are accountable to the appropriators or are the appropriators;

5. *Graduated sanctions:* Appropriators who violate operational rules are likely to be assessed graduated sanctions (depending on the seriousness and context of the offense) by other appropriators, by officials accountable to these appropriators, or by both;

6. *Conflict-resolution mechanisms:* Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials;

7. *Minimal recognition of rights to organize:* The rights of appropriators to devise their own institutions are not challenged by external governmental authorities;

8. For CPRs that are parts of larger systems: *Nested enterprises:* Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.

These conditions are rarely naturally present. The challenge is to either devise institutional arrangements that promote the establishment of those conditions or meet the governance challenges that the absence of ideal conditions create (Dietz et al., 2003). These "design principles" are drawn from the experience of local and regional CPR management. Their application at a global level to manage large CPRs is a challenge (E. Ostrom et al., 1999). Mcginnis and Ostrom (2008, p. 198) summarize this concern:

> "Scholars have found that when groups are relatively small, engage in face-to-face communication, and build norms of trust and reciprocity, they are able to agree on a strategy to solve social dilemmas and carry through on their agreements. [...] A key question for global governance, then, is whether mechanisms exists to enable resource users and other facing social dilemma to scale-up to a larger unit where face-to-face communication with all participants is impossible."

To alleviate the difficulties posed by the management of global CPRs, the use of "adaptive governance" has been advocated (e.g., Dietz et al., 2003; Folke et al., 2005). Dietz et al. (2003, p. 1907) argue:

> "Devising ways to sustain the earth's ability to support diverse life, including a reasonable quality of life for humans, involves making tough decisions under uncertainty, complexity, and substantial biophysical constraints as well as conflicting human values and interests. Devising effective governance systems is akin to a coevolutionary race. A set of rules crafted to fit one set of socioecological conditions can erode as social, technological developments increase the potential for human damage to ecosystems and even to the biosphere itself. Furthermore, humans devise ways of evading governance rules. Thus, successful commons governance requires that rules evolve."

Adaptive governance is an institutional arrangement, including rules and their enforcement mechanisms, that evolves and adapts to the changes in our knowledge and understanding of a CPR and in the CPR itself. This concept of governance is not limited to a CPR but can address the overall commons in which it is embedded. In this framework, the strategies developed to address large-scale CPR management problems include: "dialogue among interested parties, officials, and scientists; complex, redundant, and layered institutions; a mix of institutional types; and designs that facilitate experimentation, learning, and change" (Dietz et al., 2003, p. 1907).

B.4 Near-Earth orbital space as a common-pool resource

Near-Earth orbital space has been characterized as a global commons facing a collective action problem by numerous authors (see, e.g., Kurt, 2015; J. B. Taylor, 2011). From this perspective, Shackelford (2014, p. 433) analyzes to which extent space governance is "transitioning from a multilateral system centered on the United Nations to a polycentric regime complex" and if this emerging governance system can mitigate the collective action problem of space debris. B. C. Weeden and Chow (2012) and Johnson-Freese and Weeden (2012) have characterized near-Earth orbital space as a CPR and discussed the presence or absence of Ostrom's eight "design principles." Their research has highlighted that "[e]xisting mechanisms are lacking in terms of including relevant appropriators, definition of rights and responsibilities according to capabilities, and decision-making structures and enforcement mechanisms" (Johnson-Freese & Weeden, 2012, p. 80). Graduated sanctions are required but cannot be implemented without restricting space users' freedom of access. They also identify the enhancement of SSA cooperation as a crucial requirement for sustainable management of near-Earth orbital space: "Shared or cooperative SSA will play a key role in monitoring resource appropriators and verifying adherence to norms of behavior; however this is a politically distant end state from today's atmosphere of data protection, secrecy and mistrust" (Johnson-Freese & Weeden, 2012, p. 80).

C Per user cost of end-of-life services

Requiring space operators to purchase end-of-life (EOL) services for their failed satellites impose a cost on them. To assess the burden operators would face, I evaluate the cost per customer of such a requirement. If the per-customer cost is low enough, it can easily be passed on to customers without significantly affecting the company's profitability. I develop a simple model to estimate the per-user cost of EOL services for a OneWeb-like constellation. I assume that the constellation has 648 satellites, which are all launched at the same time. The satellites have a lifetime of 5 years and are de-orbited if they are still functional at the end of their design life. The reliability of the satellites as a function of time $t \geq 0$ is modeled using a Weibull distribution

$$R(t) = \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right]. \tag{C.1}$$

The failure rate $\lambda(t)$, i.e., the number of satellites failing per year, is

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}, \tag{C.2}$$

where the parameters $\beta = 0.2519$ and $\theta = 893150.6$ are taken from the maximum likelihood estimation of a single Weibull fit for small satellites ($\leq$ 500 kg) conducted by Dubos et al. (2010). Using Equation C.2, I derive the number of satellites lost each year. This number is rounded, and the residual added in the last year of the constellation's five year lifetime. At the end of every year, EOL missions remove the failed satellites from orbit. Mission architectures are not modeled, and the cost of removal is assumed on a per satellite basis. The cost of removing the first satellite C_1 ranges from USD 3 M to 9 M. Due to the learning effect, the per satellite cost of removal is expected to decrease. The cost of removing the n-th satellite is

$$C_n = C_1 \cdot n^{\log_2 b}, \tag{C.3}$$

where $1 - b$ is the unit cost reduction with each doubling in the cumulative number of removals.

The initial cost C_1 can seem rather low compared to the estimates mentioned in § 3.3.4. However, I assume that institutional actors have assumed the large research, development, test, and evaluation costs in demonstration missions (e.g., ClearSpace-1) and that multiple objects will be removed at the same time. Moreover, discussions with industry experts have confirmed the plausibility of these estimates. Wertz and Larson (1991) recommend to use $b = 95\%$ for 1–10 units, $b = 90\%$ for 11–50 units, and $b = 85\%$ for 50 or more units. As I assume that the steep initial learning has already occurred during the institutionally funded missions, I adopt $b = 90\%$.

The monthly per-user cost of these EOL services is presented on the left panel of Figure C.1 for four initial removal cost C_1. On the top right panel, the cost of each removal is presented, and on the bottom right panel, the monthly failure rate is depicted. Testing the sensitivity of each parameter, including a discount rate, highlights that the key variable determining the cost per user is the number of users of the constellation.

To estimate the number of users of the services provided by the OneWeb-like constellation, I rely on estimates of the total system throughput derived by del Portillo et al. (2019). Assuming the satellites do not have inter-satellite links, they estimate the total system throughput of the OneWeb constellation to be 1.42–1.54 Tbps, depending on the number of ground stations. They also assume that the average data-rate requested per user is 300 kbps. Thus, the constellation can serve between 4.7 and 5.1 M users. In this range, the monthly per-customer cost is well below USD 1 (as shown in the left panel of Figure C.1). For comparison, SpaceX could be charging around USD 80 monthly fees for its satellite broadband internet service (Erwin, 2019). A USD 1 per-customer cost would thus be manageable.

The demand for satellite broadband internet could be potentially lower than the number of users the constellation can serve. To verify this, I estimate the demand for such service in the US using three datasets: (i) residential fixed internet access service connections per 1000 households by census tract (FCC, 2019), (ii) number of households per census tract (U.S. Census Bureau, 2010), and (iii) number of households per income tier at the census tract level (U.S. Census Bureau, 2017). Using datasets (i) and (ii), I derive the number of households per census tract without a 200 kbps connection in at least one direction. This underserved population

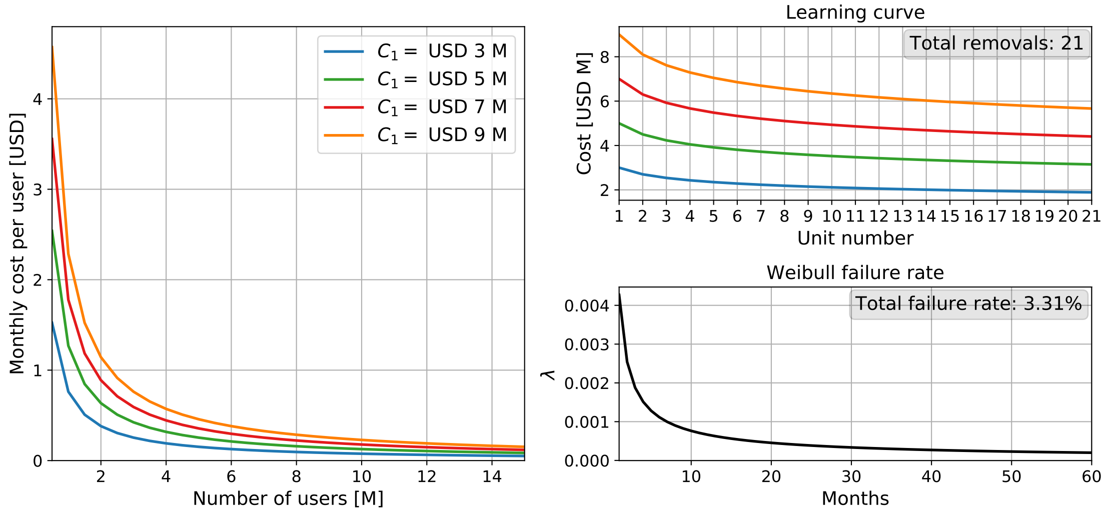

FIGURE C.1 – *Left panel:* Monthly per user cost for removing failed satellites of a OneWeb-like constellation for four initial removal cost C_1. *Top right panel:* Cost of each removal due to learning effect. *Bottom right panel:* Failure rate as a function of time.

is the main target of satellite broadband internet services.[1] However, it is unclear if those people do not have internet access because they cannot afford it, because the service does not reach their house, or because they do not want it. I neither have data on the availability of connections nor on the willingness to buy the service, but I have income data. Thus, I rely on the latter and specify an income threshold above which underserved households can afford satellite broadband internet. As I do not have income data at the household level, I can make two assumptions: either the underserved population is equally distributed among income groups, or it is found in the lowest income groups. The resulting demand for satellite broadband internet with those two assumptions as a function of the income threshold is shown in Figure C.2. If all the about 5 M users of the constellation need to be found in the US, and only people without a 200 kbps connection in at least one direction buy the service, the minimum household income to buy the service would have to be between USD 25,000 and 100,000. The lower bound is if the underserved population is in the lowest income groups and the upper bound is if the underserved population is equally distributed among income groups.

Too many assumptions and simplifications were required to derive the per-user cost of removing failed satellites from a OneWeb-like constellation. However, once more data is available, this approach could be applied to derive per-user costs. This

[1]Depending on the service and price offered by satellite internet constellations, the target market could be all internet users.

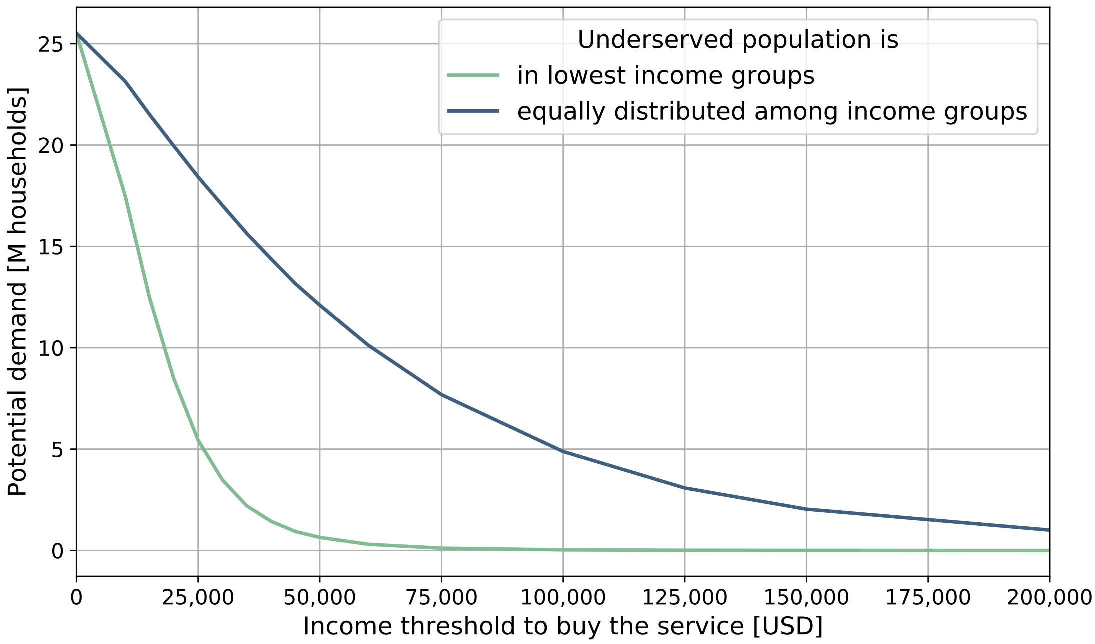

Figure C.2 – Potential demand for satellite broadband internet in the US under two assumptions regarding the distribution of households without a connection of 200 kbps in at least one direction (underserved population).

is an appropriate way of quantifying the size of the burden of cleaning orbits to operators.

D Theoretical economic models of space debris

Adilov et al. (2015) are the first to propose a theoretical economic model applied to orbital debris. They construct a two-period model where firms and consumers are modeled using a Salop (1979) circle. At the beginning of the first period, there is no debris and no satellites in space. In the first period, firms simultaneously choose whether or not to launch a satellite. The amount of debris generated is proportional to the number of launches. At the end of the first period, a fraction of the satellites is destroyed by the debris. In the second period, no new satellites are launched. Firms receive revenues in both periods from their operational satellites. Using this model, they compare the equilibrium number of launches produced when competitive firms choose their launch rate to the one obtained when a social planner maximizes the discounted sum of expected firm profits and consumer surplus. This comparison shows that competitive firms launch more satellites than the social optimum. In the second part of the paper, they relax the assumption of homogeneous debris creation and let firms choose the launcher technology and thus the amount of debris they are creating. With this second model, both the social planner's optimal rate of debris creation and launch rate are lower than the competitive rates. Competitive firms do not take into account the negative externality their launches impose on others resulting in more launches and underinvestment in debris mitigation technologies than socially optimum. They finally show that there exists a tax schedule that induces competitive firms to choose the socially optimal level of launches and debris creation rate. This tax schedule has two components: a per launch tax and a tax dependent on the level of debris creation. Adilov et al. (2015) suggest that the proceeds of the Pigouvian tax be used to finance the retrieval of space debris. Although they show the existence of such a tax schedule, they acknowledge that this might not be the optimal pricing mechanism.

The same authors develop a dynamic model of space debris, which suggests the occurrence of an "economic" Kessler syndrome before the "physical" Kessler syndrome (Adilov et al., 2018). The increasing amount of orbital debris may render space economically unusable before it becomes physically unusable. Their model predicts that at a low level of space debris, the launch rate increases at an increasing rate (as firms replace lost satellites), but as the level of space debris increases, the launch rate increases at a decreasing rate (a smaller fraction of satellite are replaced). Above a certain threshold in the number of debris, the launch rate decreases because the marginal revenue from launching has decreased (see Adilov et al., 2018, Figure 1). At some point, launching satellites is no longer profitable, and launches stop. However, debris continues to accumulate, and their number continues to increase once launches have ceased.

Adilov et al. (2019) further this study by simulating future economic activity in space and its contribution to orbital debris levels (albeit without providing many details on the model) and argue that "the economic 'tipping point' is highly unlikely to occur in the near to medium term because it requires a level of business activity in orbital space which is at least hundreds of times in magnitude greater than the current level of economic activity" (Adilov et al., 2019, p. 3).[1]

Macauley (2015) develops a similar model to the one proposed by Adilov et al. (2015). She provides numerical estimates of the externalities resulting from large and small debris generation in a static one-period model, with one type of spacecraft, and one government sector. Mitigation strategies available in the model are maneuvering capability, "graveyarding" capability,[2] and shielding. Each strategy affects the frequency and severity of debris collisions. The government designs a tax schedule to incentivize the use of the mitigation strategies available. The tax is levied at launch based on an ex-ante estimation of debris creation, with or without an ex-post rebate upon evidence of compliance with debris management requirements through graveyarding or maneuvering. As the ex-ante estimation of the probability that maneuvering and graveyarding capabilities will perform successfully is subject to high uncertainty, the strategy involving ex-post rebates is more cost-effective.

A broader model is proposed by Grzelka and Wagner (2019), who consider the decisions of a representative satellite-producing firm in a competitive market which can choose two inputs: ex-ante care, A, and ex-post or take-back care, T. They examine the firm's decisions in "any particular steady-state period that is long enough to capture the expected cradle-to-grave lifecycle of a satellite" (Grzelka & Wagner, 2019, p. 322) and assume that its revenue increases at a decreasing rate in both inputs A and T (see their Equation 1). Thus satellite-producing firms have an incentive to invest in A and T but underinvest as they cannot

[1] However, note that the "physical" tipping point of the Kessler syndrome would happen before such an "economic" tipping point.

[2] Moving spacecraft to a high-altitude orbit or destroying them through controlled atmospheric reentry.

reap the entirety of the benefits from those investments. Assuming that firms can internalize all the benefits from their investments, they calculate the socially optimal combinations of A and T. They investigate policy mechanism which allows moving from the privately optimal to the socially optimal combinations of those two parameters. They acknowledge that, theoretically, Pigouvian taxes or cap-and-trade mechanisms can fully internalize the benefits from ex-ante and ex-post care but are not institutionally feasible. Moreover, command-and-control approaches are deemed "not incentive-compatible to private firms" (Grzelka & Wagner, 2019, p. 8). Thus, they examine other Pareto-improving mechanisms. First, they argue that, albeit aligning the privately and socially optimal level of input consumption, Pigouvian subsidies may not be politically feasible or could not be implemented due to the lack of appropriate institutions, and require renewal in every time period. Secondly, they propose three decentralized mechanisms which could potentially lead to a Pareto-improvement by increasing the internalization of the benefits :

1. *Strengthening intellectual property rights:* They argue that innovators are usually not able to capture and monetize the benefits of their innovations fully. Thus, strengthening intellectual property rights could increase the benefits a firm can capture when investing in research and development in input technologies A and T. However, they note that the newly acquired market power due to stronger intellectual property rights could create a deadweight loss and favor incumbents.

2. *Clarifying intellectual property rights:* Numerous uncertainties regarding property rights (especially linked to private and commercial activities) exist in the outer space context. Given the absence of provisions regarding intellectual property rights in the international space treaties, Ro et al. (2011) address the uncertainty regarding the application of national patent laws to outer space patent disputes. Clarifying intellectual property rights could help internalize the benefits form ex-ante and ex-post care investments in the same way as strengthening them would.

3. *Promoting satellite debris take-back initiatives:* National governments or NGOs can promote satellite debris take-back initiatives by making more salient the benefits (or the absence of costs) for the firms when undertaking them. By doing so, they reduce transaction costs. Three mechanisms can help reduce them: Firstly, firms may overestimate the cost of T, and society would benefit from disseminating the true cost of T. Secondly, there might be barriers to cooperation among firms interested in tack-back initiatives, as antitrust regulators might misperceive their collaboration. Easing collaboration between interested firms might yield significant economies of scale in

take-back programs. Thirdly, policies enabling the outsourcing of ex-post care enable the reduction of the per-unit cost of T.

Although insightful, the proposals made by Grzelka and Wagner (2019) seem to overestimate the benefits to firms of investing in ex-post care. Furthermore, by focusing on the political feasibility of the measure, they seem to lose sight of the effectiveness of their policy proposals. Clarifying and strengthening property rights, and promoting derelict retrievals will have strictly no effect if operators face no cost when leaving a defunct satellite in-orbit.

More recently, Rao et al. (2020) developed a model combining orbital dynamics and satellite economics to quantify the benefit from an international Pigouvian tax on orbital use compared to a business-as-usual scenario and a scenario with ADR. Using this model, they project that introducing a tax on orbital use in 2020 would increase the net present value of the satellite industry from around USD 600 B to around USD 3 T. The optimal fee starts at USD 14,900 per satellite-year in 2020 and reaches around USD 235,000 per satellite-year in 2040. They also show that when assuming costless ADR, this scenario can only recover up to 9.5% of the value lost under the business as usual scenario.

E | Performance bond for successful disposal

The performance bond for successful disposal proposed by the FCC (see § 5.5 and § 6.2.3) directly incentives operators to avoid unplanned debris creation and successfully remove their satellites from orbits. However, if operators must immobilize a large amount of money or pay large surety bonds fee, the mechanism might impede innovation and lessen the growth of the space economy. New space ventures can be hard to finance, and such a burden might hamper their development. The amount of the bond could be reduced and coupled with ongoing fee payments to alleviate this problem.

I explain this approach through an example. Let us imagine that an operator obtains a license for a constellation of 700 spacecraft orbiting at 1,000 km and weighing 150 kilograms, promising a successful disposal rate of 95%. Given the FCC's proposal, the operator would have to pay USD 15.75 M per year per predicted year in orbit above 25 years. This would be more than a potential cap set by the FCC. Let us assume this cap is set at USD 100 M. If I assume debris is generated only through the loss of spacecraft, the operator will have a share of the bond forfeited once it loses more than 35 spacecraft. The mean of the remaining years in orbit for the failed satellites is greater than 200, which is the cap proposed by the FCC. Thus the forfeited amount per spacecraft lost above 35 is USD 26,250. This seems rather low compared to the value of the bond. The value of the bond B (see Equation 6.4) can be adapted as

$$B_c = c \cdot B = c \cdot M_T \cdot (Y - 25) \cdot O_T, \tag{E.1}$$

where $c \in [0, 1]$, and require an ongoing fee payment. Let us assume $c = 0.3$, and the cap is reduced to USD 30 M. In this case, our hypothetical operator is required to pay USD 30 M upfront (assuming a deposit and refund scheme). However, once it has lost more than the 35 'planned' spacecraft, the operator has to pay a fee equal to USD 26,250 per spacecraft lost, collected on a yearly basis. This fee is required until the amount of the fees paid reaches $(1 - c) \cdot B$. With this approach, there is no longer a cap, and operators will have to pay commensurately with the increased risk they created. The constant c is the balance for the regulator between a high burden on operators before launch and the risk of no payment. It could potentially be set differently depending on the type or financial standing of the operator.

F | Public opinion regarding space debris

If remediation is to be financed by governments, public opinion regarding space debris is of utmost importance. Indeed, in democratic countries, public opinion has a substantial impact on public policy, and the salience of an issue enhances this impact (Burstein, 2003). In the space policy context, Steinberg (2011) showed that NASA's funding is responsive to public opinion. However, knowledge of the awareness level in the general population regarding the space debris problem and the willingness to take action is lacking.

Given the rather technical nature of space debris remediation and the expected low awareness level in the general population, running a representative survey is not feasible. In a recent review of data and methods employed in the quantitative space policy literature, Pomeroy (2019) advocates for the use of the textual content produced on social media platforms to study public opinion regarding space policy. The use of text-as-data and automatic content analysis methods have been recognized as a method of choice in political science to address topics that suffer from data scarcity issues (Grimmer & Stewart, 2013).

To assess the content and size of the public debate around space debris, I revert to public information readily available online. Similarly to Whitman Cobb (2015), who uses Google Trends[1] and Twitter[2] data to measure interest in space policy in the American public, I use data from these two mediums. Google Trends enables its users to gather data on Google search frequencies. For a given time frame and in a defined location, the tool returns how frequently a given term has been searched for relative to the total number of searches performed on Google. Tweets offer finer granularity than simple internet searches as they contain contexts. This medium gives more detail on what people are interested in or doing.

[1] See https://trends.google.com.
[2] See https://twitter.com/.

In this short preliminary study, I aim to show to what extent data from these two mediums can give insights into the salience of the space debris issue and the content of the public debate surrounding it. However, I detail neither the methodological pitfalls arising when using those two data sources nor the methodology and algorithms used.

F.1 Google Trends

Google Trends can be used to measure the salience in the public sphere of the space debris problem and make comparisons with other issues that compete for attention. Although there are some methodological pitfalls in using Google Trends, this enables comparisons across location and time of the relative search interest for a topic (see, e.g., Mellon, 2013, for a discussion on the advantages of using internet searches in measuring salience and the methodological issues). The use of this method has been validated for some topics. By testing weekly Google search data against Gallup's "most important problem" question,[3] Mellon (2014) found that the salience of four issues, fuel prices, the economy, immigration, and terrorism, can be measured in the US using search data.

Google Trends pools together related search queries under "topics," which removes the restriction to a single search term (and thus to a single language) and enables worldwide comparisons. On the left panel of Figure F.1, the worldwide relative search interest for five topics—space debris, marine pollution, hazardous waste, deforestation, and acid rain—between the beginning of 2004 and the end of 2019 is displayed. The search interest is normalized on a 0–100 scale, where 100 is the maximum search interest for the time frame selected. The level of search interest for space debris remains fairly stable over time and is of the order of the one for marine pollution. Deforestation, hazardous waste, and acid rain drive, on average, 15 times more searches. The difference between these topics and space debris has reduced over time, but this is due to relatively fewer searches related to these topics than an increase in searches related to space debris. On the right panel of Figure F.1, the share of searches for the five topics in the main spacefaring nations (except China) is displayed. The share of searches devoted to space debris is fairly similar across countries, except Japan, where the topic space debris drives about seven times more searches. The lack of information regarding the terms encompassed by a topic in each language and the methodology used by Google Trends prevent us from deriving an explanation for this difference. Astroscale, one of the leading

[3] Gallup is an American company conducting public opinion polls.

F.1. Google Trends

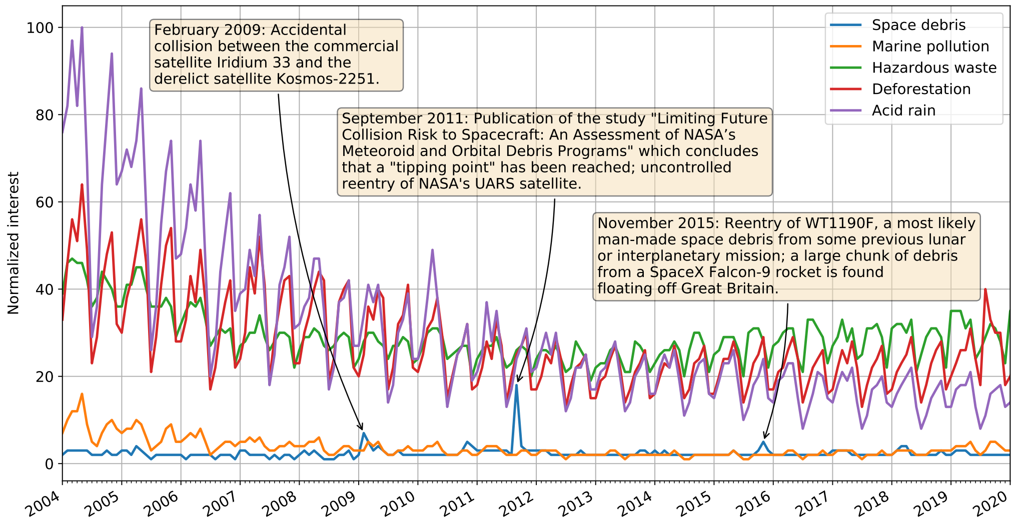

FIGURE F.1 – *Left panel:* Google Trends worlwide relative search interest for five selected topics. *Right panel:* Relative search interest for the same topics broken down by countries.

companies developing EOL services, is Japanese and could be a reason for the higher share of searches in Japan. However, I have no way to test this postulate.

The interest in the space debris topic shows three peaks which are worth investigating. A better understanding of the dynamics of public attention around this topic can help improve future communication and raise awareness on the topic. The first peak can be confidently linked to the collision between the operational commercial satellite Iridium 33 and the derelict Russian military satellite Cosmos-2251. This was the first event of this scale and drove considerable attention to the problem. The second peak is by far the highest relative search interest recorded. However, linking it to a single event is not straightforward. During this month, two notable events happened: NASA published its report "Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs" (National Research Council, 2011) which warned that the space debris environment had reached the "tipping point" of the Kessler syndrome and NASA's Upper Atmosphere Research Satellite (UARS) reentered Earth's atmosphere. This event drove considerable media attention because NASA predicted that large parts of the satellite might reach the ground and could potentially crash on inhabited regions.

The last peak in search interest for space debris coincide with two events: the reentry of WT1190F, a piece of space debris identified as the remains of a rocket motor that propelled a NASA probe to the Moon in 1998 (Watson, 2016), and the discovery of a large chunk of debris from a SpaceX Falcon-9 rocket floating off the coast of Great Britain. Due to its reentry angle resembling the one of an asteroid, the reentry of WT1190F interested scientists and drove media attention. Peaks of public attention for space debris appear driven by major events related to space debris such as in-orbit fragmentations or object reentries. Although the space debris problem has escalated over the period 2004–2019, public attention for space debris, as measured by Google Trends, has not increased.

F.2 Twitter

To obtain more granular data regarding public opinion on space debris, I revert to Twitter data. I gathered all the tweets containing the keywords "space" and "debris" for which the identified language is English and which have been published between January 22 and February 18, 2020.[4] By manually screening the most retweeted tweets, the ones unrelated to the topic were removed. This yielded a dataset of 5,611 tweets, out of which 3,497 are retweets.[5]

The number of tweets published daily is presented in Figure F.2, alongside important events related to the topic that help explain the trends. The close approach between the Infrared Astronomical Satellite (IRAS) and the Gravity Gradient Stabilization Experiment (GGSE-4), two defunct satellites, drove considerable media attention and led to a significant amount of tweets. Such attention for a rather common event (the conjunction between large objects in-orbit) is unusual. This highlights that efficient communication on conjunction events can drive the public interest and could be a way of raising awareness on the space debris issue.

Further analysis of the tweets' content using topic modeling (with latent Dirichlet allocation; Blei et al., 2003) and sentiment analysis gave only little insight into the public debate surrounding space debris. I do not think these results are worth detailing here. However, I spent only a very limited amount of time on this analysis, and I believe that further research on the topic using similar methods is worth undertaking.

[4]The library `searchtweets`, a python wrapper for the Twitter premium search API, is used for this task.

[5]As a retweet helps broadcast the content of the original tweet, I keep them into account in the same way as a tweet.

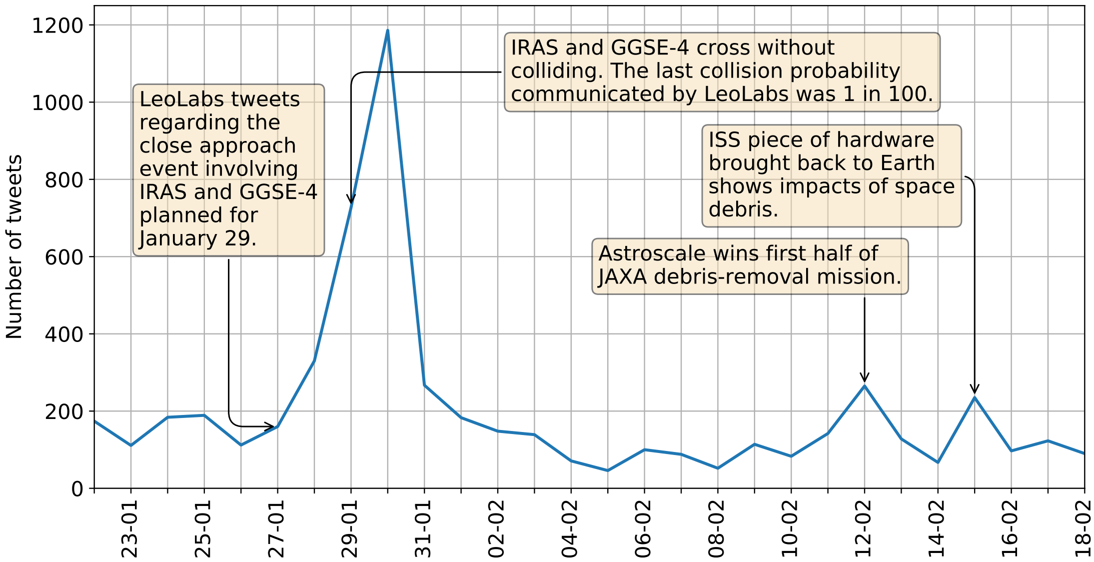

FIGURE F.2 – Number of tweets published daily between January 22 and February 18, 2020, containing the keywords "space" and "debris" for which the identified language is English.

Acronyms

ADR Active Debris Removal.

ASAT Anti-SATellite.

CAGR Compound Annual Growth Rate.

CONOPS CONcepts of OPerationS.

CPR Common-Pool Resource.

CRD2 Commercial Removal of Debris Demonstration.

DES DiEthylStilbesterol.

DoC Department of Commerce.

DoD Department of Defense.

EMR Energy-to-Mass Ratio.

EOL End-Of-Life.

ESA European Space Agency.

ETS Emissions Trading Scheme.

EU European Union.

FAA Federal Aviation Administration.

FCC Federal Communications Commission.

GEO Geostationary Earth Orbit.

GHG GreenHouse Gas.

GSO Geostationary Satellite Orbits.

IADC Inter-Agency Space Debris Coordination Committee.

IOS In-Orbit Servicing.

ISO International Organization for Standardization.

JAXA Japan Aerospace Exploration Agency.

JCA Just-in-time Collision Avoidance.

LC Liability Convention.

LEO Low Earth Orbit.

MASTER Meteoroid and Space Debris Terrestrial Environment Reference.

MEO Medium Earth Orbit.

NASA National Aeronautics and Space Administration.

NGSO Non-Geostationary Satellite Orbits.

NOAA National Oceanic and Atmospheric Administration.

NPRM Notice of Proposed RuleMaking.

NPV Net Present Value.

NSS National Space Strategy.

ODMSP Orbital Debris Mitigation Standard Practices.

ORDEM Orbital Debris Engineering Model.

OST Outer Space Treaty.

PD Prisoner's Dilemma.

PMD Post-Mission Disposal.

PwC PricewaterhouseCoopers.

SEM Space Environment Management.

SPD-2 Space Policy Directive-2.

SPD-3 Space Policy Directive-3.

SSA Space Situational Awareness.

SSN Space Surveillance Network.

STM Space Traffic Management.

TEV Total Economic Value.

TPL Third-Party Liability.

UK United Kingdom.

UN United Nations.

UNCOPUOS United Nations Committee on the Peaceful Uses of Outer Space.

US United States.

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