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POUR OBTENIR LE GRADE DE
DOCTEUR
DE L'UNIVERSITÉ DE BORDEAUX
ÉCOLE DOCTORALE ENTREPRISE, ÉCONOMIE ET
SOCIÉTÉ

SCIENCES ECONOMIQUES

Par **Julien GUYOT**

Analyse économique de l'exploitation de l'orbite terrestre

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Soutenue le 24 Juin 2024

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Mots-clefs : Économie spatiale, Environnement, Soutenabilité, Pollution, Satellites, Constellations, Biens communs

Avec l'avènement de la nouvelle ère spatiale, le nombre de lancements annuels de satellites a fortement augmenté, exacerbant ainsi la problématique des débris spatiaux. D'un côté, les services rendus par les satellites viennent structurer bon nombre d'applications nécessaires à notre économie moderne. De l'autre, l'orbite terrestre, toujours plus exploitée, voit son stock de débris croître, menaçant ainsi de collisions un nombre toujours plus grand de satellites ; qui augmenteraient à leur tour ce nuage de pollution matériel. À plus long terme, ces débris pourraient faire peser un tel coût sur le secteur spatial que l'économie mondiale pourrait en être significativement affectée. Plus largement, la question de la soutenabilité de l'industrie spatiale et de l'accès à l'espace représente un enjeu de recherche majeur de ce siècle. Cette thèse a pour objectif d'étudier l'exploitation de l'orbite terrestre et d'identifier les outils économiques qui permettraient d'en faire un usage optimal.

Cette thèse s'appuie sur trois travaux. Les deux premiers présentent un modèle analytique simplifié de l'exploitation de l'orbite terrestre basse à long terme en s'appuyant sur l'article de Rouillon (2020). Dans le modèle du premier papier est introduit une variable de conception se matérialisant par la durabilité d'un satellite, ainsi que la possibilité de nettoyer chaque année l'orbite d'une part de ses débris. Le deuxième travail s'intéresse à l'impact du choix de l'altitude à laquelle les opérateurs choisiront d'opérer leurs satellites. Ce choix a deux impacts majeurs. D'abord, plus un satellite est lancé haut, plus les débris pouvant résulter de son opération pourront rester longtemps en orbite. Ensuite, la verticalité de l'orbite, c'est-à-dire le fait que des objets envoyés plus hauts peuvent menacer ceux se trouvant plus bas, vient elle-même peser sur la gestion de cet espace et sur les instruments incitatifs à utiliser. Enfin, un dernier travail se concentre plus spécifiquement sur les nouvelles grandes constellations et à la manière dont une concurrence imparfaite impacte l'utilisation de l'orbite. Les interactions stratégiques entre ces grands opérateurs sont ainsi analysées.

Les principaux résultats de ces recherches sont les suivants. Le premier étant que, en l'absence de régulation, la mise en œuvre de technologies de mitigation (blindage, retraits de débris, etc.) entraîneront un effet rebond. La mise en place de contraintes ou d'incitations pesant sur le secteur spatial sont donc nécessaires de manière à exploiter efficacement l'orbite terrestre. Un second résultat est que, pour obtenir une efficacité optimale, les obligations et incitations ne devraient pas peser que sur le nombre de lancements, mais aussi sur la conception des satellites et sur le financement des retraits de débris. De plus, l'altitude à laquelle opère un satellite pèse sur les risques de collisions qu'il engendrera. En conséquence, le troisième résultat est que les instruments économiques employés devront eux aussi varier avec ce choix fait par son opérateur. Les résultats précédents portent sur une situation de concurrence parfaite, où les opérateurs de satellites n'ont pas de pouvoir de marché. La problématique est encore différente dans des marchés faiblement concurrentiels, tels que celui des nouvelles grandes constellations de satellites, dont l'objectif est de potentiellement couvrir la planète entière de manière à rendre accessible internet même dans les zones les plus reculées. Dans ce cas, il est en effet attendu qu'un faible nombre d'acteurs assurent l'offre de ce type de service. Ainsi, le quatrième et dernier grand résultat est qu'une concurrence duopolistique non régulée est moins efficace qu'un service public mondial ne le serait, et il est montré à quel point les dommages environnementaux peuvent aggraver le différentiel entre ces deux situations.

Résumé en Anglais : Economic analysis of Earth orbital exploitation

Keywords: Space economics, Environment, Sustainability, Pollution, Satellites, Constellations, Common goods

With the advent of the new space age, the number of annual satellite launches has risen sharply, exacerbating the problem of space debris. On the one hand, the services provided by satellites are at the root of many of the applications required by our modern economy. On the other hand, the Earth orbit is increasingly used, and its stock of debris is growing, threatening an ever-increasing number of satellites with collisions, which would in turn increase this cloud of material pollution. In the longer term, this debris could become so costly to the space sector that the world economy could be significantly affected. More broadly, both the questions of the sustainability of the space industry and the future of the access to space represent a major research challenge of this century. The aim of this thesis is to study the management of the Earth's orbit and to identify the economic tools that would enable its optimal use.

This thesis is based on three works. The first two present a simplified analytical model of the long-term exploitation of low-Earth orbit based on Rouillon's paper (2020). The first work introduces a design variable in the form of a satellite's durability, as well as the possibility of cleaning the orbit of some of its debris each year. The second work examines the impact of the altitude at which operators choose to operate their satellites. This choice has two major impacts. Firstly, the higher a satellite is launched, the longer any debris resulting from its operation can remain in orbit. Secondly, the verticality of the orbit, i.e. the fact that objects sent higher can threaten those lower down, also influences the management of this space and the incentive instruments to be used. Finally, the last work focuses more specifically on the new large constellations and how imperfect competition impacts orbit utilisation.

This research has led to several key findings. The first is that, in the absence of regulation, the implementation of mitigation technologies (shielding, debris removal, etc.) will cause a rebound effect. The introduction of constraints or incentives on the space sector is therefore necessary if Earth orbit is to be exploited efficiently. A second result is that, for optimum efficiency, obligations and incentives should not only weigh on the number of launches, but

also on satellite design and the financing of debris removal. Furthermore, the altitude at which a satellite operates has an effect on the risk of collisions it generates. Consequently, the third result is that the economic instruments employed will also have to vary with the altitude chosen by the operator. The preceding results apply to a situation of perfect competition, where satellite operators have no market power. The problem is even different in markets with little competition, such as the new large satellite constellations, whose aim is to potentially cover the entire planet, making the Internet accessible even in the most remote areas. In this case, a small number of players are expected to provide this type of service. The fourth and final major result is that unregulated duopolistic competition is less efficient than a global public service. It is also demonstrated that the magnitude of the environmental damages resulting from the launch of a satellite increase the gap between those two situations.

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Chapter 1

General introduction

1.1 The Earth’s orbit, the satellites, and their economics

In its latest report, the satellite industry association (State of the Satellite Industry Report, SIA (2023)) estimated the value of the global “space economy” to be roughly \$384 billion in 2022. Among it, the satellite industry represented \$281 billion. Still, these figures hardly reflect the extent to which the modern society rely on satellite services.¹ The world economy is thus increasingly dependent on the use of the Earth’s orbit, and its pollution by space debris will therefore weigh more and more heavily on its growth. Recently, Nozawa et al. (2023) estimate that, over a century, global GDP could be reduced by 0.91% if nothing is done to mitigate the proliferation of debris.

1.1.1 Artificial satellites and their applications

Satellites provide various types of services, the main ones being:

Telecommunications. These can be split into two sub-categories.

The first is network-integrated telecommunications, where communications can take place in both directions. This is the case for satellite constellations integrated into the worldwide Internet network, for example, or military telecommunications networks.

The second is broadcast networks. In this case, the direction of communication is always the same, from a broadcaster sending information to satellites, which in turn transmit the information to Earth, so that all customers receive the information. This is the case with satellite television and radio broadcasting.

Remote-sensing. This category covers all satellites that observe the Earth (producing maps, measuring sea temperatures, measuring the size of glaciers, measuring light levels in cities) and space (observing the sun, searching for exoplanets). These applications can be

¹According to a November 21, 2018 report on European space policy, an individual uses an average of 47 satellites per day in Western societies.

used for research, to provide information of direct economic value (weather forecasts for farmers, prospecting for natural resources), or for military purposes. Techniques employed are numerous, ranging from light spectrum observation (from infrared to ultraviolet), to radar or listening for radio signals.

Geopositioning. The aim of these satellite constellations is to permanently cover the Earth with their signals, so that electronic circuits can interpret them to deduce the position of an object. This service enables applications such as the guidance of people and vehicles, for both civil and military applications.

Space stations constitute a last special class. They are intended to be manned, and are involved in research.

1.1.2 Orbit classification

The Earth's orbit is generally divided into three categories:

Low Earth orbit (LEO) involves satellites orbiting at altitudes up to 2,000 kilometres. Satellites sent to these altitudes benefit from their proximity to the Earth for the applications they require. They can be divided into two main groups. Firstly, Earth observation satellites (for example, for civil and military imaging needs, or for weather forecasting), whose sensors must not be too far away, in order to achieve a satisfactory resolution. Secondly, certain communications satellites, whose quality of service requires rapid transmission of information. This is the case for the new constellations being integrated into the Internet network.

Low Earth orbit sustain the highest number of satellites, with 3797 of them in 2022 (UCS, 2022). They were distributed among 162 satellite operators. Figure 1.1 gives an overview of this distribution. A large part of the fleet was made up of the Starlink constellation, with OneWeb a distant second. Nevertheless, this orbit remains the subject of several markets with different levels of competition. In addition, all satellites do not have the same value, making the value distribution different from the one focusing on the fleet sizes (Adilov et al., 2023).

Medium Earth orbit (MEO) encompasses higher altitudes, from 2,000 to 3,586 kilometres. This category of orbit is mainly used by geopositioning satellites. Their greater distance from the Earth enables their signals to cover a wider area.²

² Eventually, however, new constellations of geopositioning satellites may be placed in low-Earth orbit. One of the main reasons for this is that, since the signal emitted by lower-altitude satellites can be more powerful once it reaches Earth, this type of constellation would be more difficult to jam. The second is economic: rather than having large, dedicated satellites in medium-Earth orbit, it is now possible to make dual use of the new large satellite constellations. It could thus be both safer and cheaper to transfer this service to the very many satellites deployed in low Earth orbit (Reid et al., 2020).

Rank	Operator	Satellite stock	Percentage of total
1	SpaceX	2219	58,44%
2	OneWeb Satellites	427	11,25%
3	PlanetLabs, In.	215	5,66%
4	Swarm Technologies	151	3,98%
5	Spire Global Inc.	124	3,27%
6	Iridium Communications, Inc.	75	1,98%
7	Chang Guang Satellite Technology Co. Ltd.	44	1,16%
8	ORBCOMM Inc.	35	0,92%
9	Globalstar	32	0,84%
10	Satellogic S.A.	26	0,68%
11	Kepler Communications	19	0,50%
12	Gonets Satcom	18	0,47%
13	ICEYE Ltd.	15	0,40%
14	Guodian Gaoke	15	0,40%
15	Aerospace Corporation	14	0,37%
16	BlackSky Global	14	0,37%
17	HawkEye 360	12	0,32%
18	Kleos Space	12	0,32%
19	Tyvak Nanosatellite Systems, Inc.	12	0,32%
20	Astrocast	10	0,26%
21-162	Autres	308	8,11%
Total		3797	100%

Table 1.1: The top 20 low Earth orbit satellite operators
Source : Union of Concerned Scientists database (UCS, 2022)

Rank	Operator	Usage	Percentage of total
1	DoD/US Air Force	Géopositionnement (GPS)	34
2	Chinese Ministry of National Defense	Géopositionnement (Beidou)	29
3	Russian Ministry of Defense	Géopositionnement (GLONASS)	29
4	European Space Agency (ESA)	Géopositionnement (Galileo)	26
5	O3b Networks Ltd.	Télécommunications	20
6	Air Force Research Laboratory	Recherche	1
7	National Reconnaissance Office (NRO)/US Air Force	Observation	1
Total			140

Table 1.2: Satellite operators in medium Earth orbit

Source : Union of Concerned Scientists database (UCS, 2022)

Satellite operators in this orbital region and their constellations are presented in table 1.2. Medium Earth orbit hosts four geopositioning satellite fleets: the GPS (the United States of America), Galileo (the European Union), GLONASS (Russia) and Beidou (China).³ Their fleets contain 26 to 34 satellites each. Apart from two satellites owned by the U.S. Army, the only other constellation in this orbit is a telecommunication one⁴, making it an orbit primarily used by the governments of major space powers.

Geostationary (Earth) orbit (GEO), extends over a range of altitudes from 35,586 to 35,986 kilometres. These altitudes enable the satellites to rotate at the same speed as the Earth, and therefore to remain permanently over the same area of the globe.⁵ This characteristic, combined with the ability to cover a large surface area, makes the latter category an orbit mainly used by broadcasting satellites.

Geostationary satellites are more evenly distributed. In total, the geostationary orbit hosted 332 satellites distributed among 87 satellite operators in 2022. However, broadcasting fleets often focus on a given part of the world where they deliver a regional service, like satellite television for a national public.

1.1.3 Economic data

Figure 1.1 shows the distribution of the \$384 billion in annual turnover estimated for the space sector. The first category (in grey) represents all space activities unrelated to the satellite industry. This includes government budgets for research and exploration, as well as emerging manned commercial spaceflight activities. The other categories, when aggregated,

³India has its own local constellation that covers its part of the planet, that consists of three satellites in geostationary orbit and four satellites in geosynchronous orbit.

⁴It provides voice and data communications to mobile operators and Internet service providers.

⁵Geostationary orbit is a subpart of geosynchronous orbit. Geosynchronous orbit is an Earth-centred orbit with an orbital period that matches Earth's rotation on its axis. Geostationary satellites are on the same plane than the Earth's equator (both inclination and eccentricity are equal to 0), such that a satellite always remains above the same point on Earth.

Rank	Operator	Satellite stock	Percentage of total
1	SES S.A.	43	12,95%
2	Intelsat S.A.	32	9,64%
3	EUTELSAT S.A.	26	7,83%
4	Russian Satellite Communications Company	14	4,22%
5	Telesat Canada Ltd. (BCE, Inc.)	11	3,31%
6	Echostar Satellite Services, LLC	11	3,31%
7	DirecTV, Inc.	10	3,01%
8	INMARSAT, Ltd.	10	3,01%
9	Sky Perfect JSAT Corporation	10	3,01%
10	China Satellite Communication Corp. (China Satcom)	10	3,01%
11	PanAmSat (Intelsat S.A.)	9	2,71%
12	Embratel Star One	7	2,11%
13	Asia Broadcast Satellite Ltd.	5	1,51%
14	Asia Satellite Telecommunications Co. Ltd.	5	1,51%
15	Turksat	5	1,51%
16	Gazprom Space Systems	5	1,51%
17	Hispamar (subsidiary of Hispasat - Spain)	4	1,20%
18	APT Satellite Holdings Ltd.	4	1,20%
19	Broadcasting Satellite System Corp.	4	1,20%
20	Hispasat	4	1,20%
21-87	Autres	103	31.02%
Total		332	100%

Table 1.3: The top 20 satellite operators in geostationary orbit
Source : Union of Concerned Scientists database (UCS, 2022)

give an estimated turnover for the satellite industry of \$281 billion a year, representing 73% of all economic activity in space.

Satellite services generate annual revenues of \$103 billion. \$92.7 billion are directly attributable to individuals, who are consumers of satellite television, satellite radio or Internet access. Business services account for \$17.7 billion in annual sales. These mainly involve access to voice and data telecommunications services within organisations, whether for fixed use (between several remote infrastructures) or mobile use (an example being merchant ships). Finally, a particular sub-category consists of the commercial operation of observation satellites, which can be offered to both legal entities (companies and other private bodies) and individuals (direct consumers).

The ground equipment category is a complementary category to the previous one. It covers all sales of terrestrial equipment directly required to operate satellite services. It includes navigation equipment using satellite geopositioning, worth an estimated \$111.7 billion annually, antennas and decoders needed to receive video (satellite television) and sound (satellite radio) for \$17.9 billion, as well as other equipment needed to connect to a satellite data network for \$15.2 billion.

Satellite manufacturing, by contrast, represents a market worth just \$15.8 billion. Nearly two-thirds of this turnover is generated in the United States of America. Of the 2,325 satellites reported as having been launched that year, 84% were communications satellites, 10% were observation satellites, and the remaining 6% were divided between R&D, defence, geopositioning and other government or military telecommunications satellites.

Launch activities, the business sector that consists in putting satellites into orbit by offering to host payloads on their space launch vehicles, also generated only a small share of the total, reaching just \$7 billion. Of the 186 launches worldwide, 161 were commercial. This activity is also dominated by the United States, where 56% of this turnover has been achieved.

Clean-up activities include everything related to the mitigation of orbital pollution. These range from launches of objects designed to remove debris from orbit, to systems designed to avoid collisions with active satellites by finding and tracking debris, as well as missions designed to extend the lifespan of artificial satellites. These activities are still in their infancy and represent a business worth less than \$1 billion a year.

Table 1.4 shows the breakdown of revenues by service type. Satellite television services have long been the highest revenue-generating service. In 2020, they were estimated to be worth \$88.4 billion, accounting for three quarters of revenues from all services combined. The second highest revenue category was data networks based on satellites in geostationary orbit, at \$15.7 billion. This was followed by satellite radio revenues of \$6.3 billion. Satellite radio accounted for \$2.8 billion in revenues. MEO and LEO data networks, which include

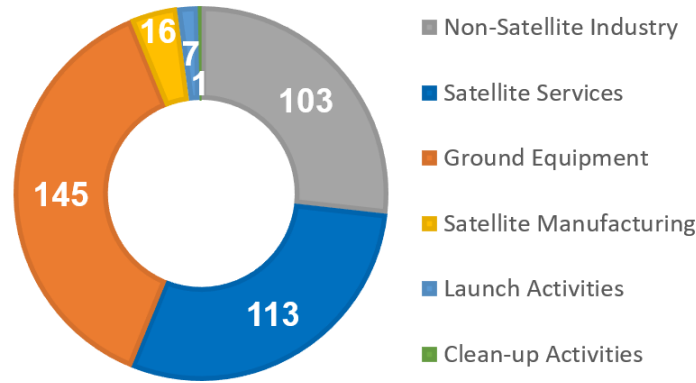


Figure 1.1: Distribution of the annual global turnover of the space industry for year 2022 (data in billions of dollars)

Source: Satellite Industry Association, 2023

the new large constellations offering Internet access that were still in the early stages of deployment, only represented an estimated \$2.6 billion in revenues. Observation satellites, fewer in number, accounted for sales of \$2.6 billion. Lastly, mobile telecoms services accounted for just \$2 billion in 2020.⁶ Overall, broadcasting services (television and radio) reported an annual revenue of \$94.7 billion, representing 80% of the total. This compares with an estimated \$20.5 billion a year for data network services, or 17.4% of all satellite services.

Major developments are currently taking place with the arrival of the new major constellations, the main and most advanced one being Starlink. Its development was announced in 2015. Since then, more than 5,000 satellites have been put into orbit to join this constellation,⁷ whose final target size is 42,000 satellites.⁸ Elon Musk said he was prepared to invest between \$20 and \$30 billion in Starlink.⁹ However, while projections were for sales of \$12 billion by 2022, only \$1.4 billion actually materialised. These new constellations, whether they be this one, supported by SpaceX, or Kuiper, supported by Amazon, remain a gamble on the future.¹⁰ The profitability of these investments will depend on the number of consumers they manage to bring on board and will be able to retain, as well as their pricing strategy.¹¹ Whatever the outcome, these major projects are already bringing about many changes for the space industry, both in terms of innovation and the projected timetable for certain space launchers.

Service type	Turnover (\$billions)
Television	88,4
Radio	6,3
Mobile	2
Fixed Satellite Services	15,7
Broadband	2,8
Remote sensing	2,6
Total	117,8

Table 1.4: Distribution of satellite service revenues in 2020 (SIA, 2021)

1.2 The space debris issue and the orbital environment

1.2.1 Earth orbit and its pollution

In the same way that the Earth faces greenhouse gas pollution causing global warming, the Earth’s orbit faces another form of global pollution: space debris. Remnants of former space missions, as well as fragments resulting from collisions and anti-satellite missile tests, ranging in size from a few millimetres to several metres in diameter, are all out-of-control objects which, as they orbit our planet at more than 28,000 km/h, create a risk of collision. Collisions between these objects only increase the amount of debris in orbit. This in turn increases the risk of collision for satellites that are still operational, which ultimately has repercussions for players in the space sector. This effect is commonly known as a (negative) externality.¹²

This negative externality comes in the form of costs imposed on public and private players in the space sector. Adilov, Alexander and Cunningham (2020) draw up a list of such costs. The first are direct losses, linked to the reduction in the average lifespan of satellites or the loss of functionality. The second are indirect and financial, taking the form of an increase in

⁶In 2014, they were estimated at \$3.3 billion.

⁷This figure was obtained from the statistics table provided by astrophysicist Jonathan McDowell accessible at: <https://planet4589.org/space/con/star/stats.html>.

⁸The figure of 42,000 satellites appeared in a FCC (2021) commission report accessible at: <https://docs.fcc.gov/public/attachments/FCC-21-48A1.pdf>.

⁹These figures concerning Starlink’s investment forecasts and turnover are reported by Jérôme Marin in a 2023 press article for the journal *l’usine digitale*, accessible at <https://www.usine-digitale.fr/article/starlink-franchit-une-etape-vers-la-rentabilite.N2190868>.

¹⁰See Daehnick et al. (2020) for an analysis of this issue.

¹¹Badikov and Zaytsev (2023) estimate that Starlink would need to attract at least three million new consumers each year in order to become profitable.

¹²Pigou (1920) stated a situation of market failure such that: “One person A, in the course of rendering some service, for which payment is made, to a second person B, incidentally also renders services or disservices to other persons [...], of such a sort that payment cannot be exacted from the benefited parties or compensation enforced on behalf of the injured parties.” (p. 183). Today, these services (disservices) are called positive (negative) externalities, or external benefits (costs). These unpriced effects on third parties, if correctly evaluated, can be priced under the form of a “Pigouvian” tax (subsidy or negative tax). Doing so is referred as “internalising the externality”.

Type	Description	Definition
PL	Payload	Space object designed to perform a specific function in space excluding launch functionality. This includes operational satellites as well as calibration objects.
PF	Payload Fragmentation Debris	Space objects fragmented or unintentionally released from a payload as space debris for which their genesis can be traced back to a unique event. This class includes objects created when a payload explodes or when it collides with another object.
PD	Payload Debris	Space objects fragmented or unintentionally released from a payload as space debris for which the genesis is unclear but orbital or physical properties enable a correlation with a source.
PM	Payload Mission Related Object	Space objects released as space debris which served a purpose for the functioning of a payload. Common examples include covers for optical instruments or astronaut tools.
RB	Rocket Body	Space object designed to perform launch related functionality. This includes the various orbital stages of launch vehicles, but not payloads which release smaller payloads themselves.
RF	Rocket Fragmentation Debris	Space objects fragmented or unintentionally released from a rocket body as space debris for which their genesis can be traced back to a unique event. This class includes objects created when a launch vehicle explodes.
RD	Rocket Debris	Space objects fragmented or unintentionally released from a rocket body as space debris for which the genesis is unclear but orbital or physical properties enable a correlation with a source.
RM	Rocket Mission Related Object	Space objects intentionally released as space debris which served a purpose for the function of a rocket body. Common examples include shrouds and engines.
UI	Unidentified	Unidentified space objects.

Table 1.5: ESA’s object classification. Source: ESA’s annual space environment report (2023).

the cost of insuring space missions. Finally, adapting to these risks induces some cost related to the designing of better protected objects, the deployment of necessary surveillance systems (Space Situational Awareness, SSA), the increase in the number of avoidance measures, and finally, the possible retrieval of debris.

1.2.2 Evolution of the orbital environment

Several types of objects are in orbit. The European Space Agency (ESA) uses the classification shown in table 1.5.

Figure 1.2 presents the evolution of all object types in all Earth orbits from the start of the space era to 2023. During this period, the number of man-made payloads (PL) has gone from 0 to almost 10,000. This has been accompanied by an increase of the number of rocket bodies (RB) that have been left in orbit after releasing those payloads. All those

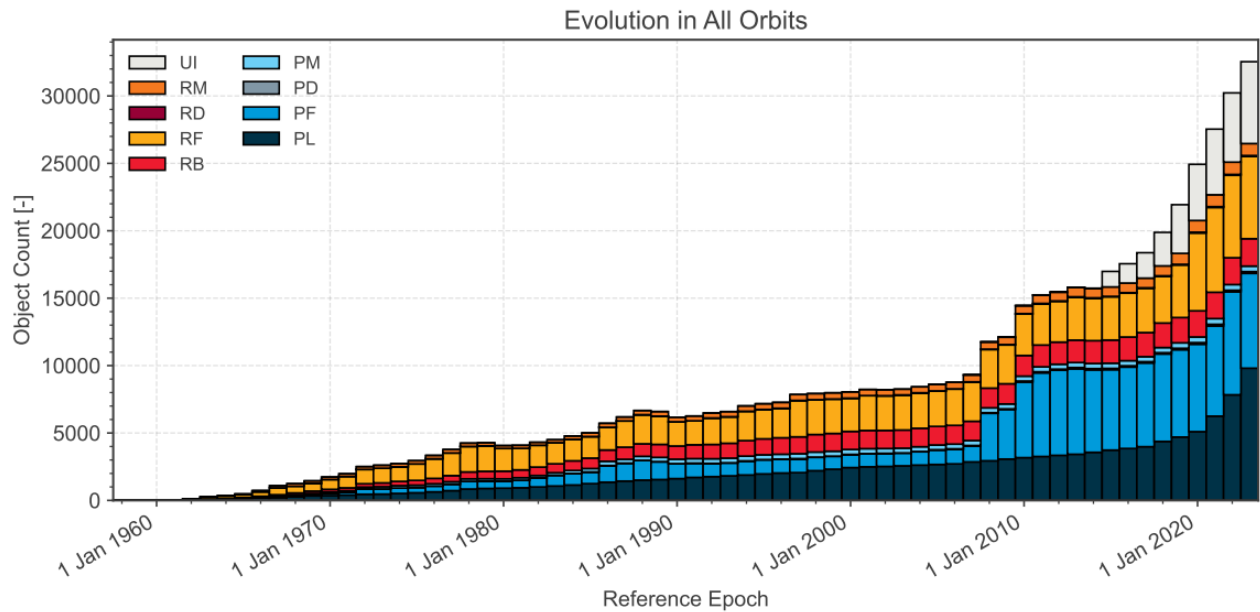


Figure 1.2: Evolution of the stocks of known objects within all orbits. Source : ESA’s annual space environment report (2023).

objects in orbit led to a number of collisions,¹³ break-ups, and deliberate anti-satellite weapon tests that resulted in the creation of a growing number of fragment debris coming from the fragmentation of payloads (PD/PF) and rocket bodies (RD,RF). Most of those registered fragment debris can be traced back from a known unique event (PF/RF). Once accounting for both the number of payload and rocket mission related objects on the one hand, and the stock of unidentified objects on the other, the total stock of known objects amounts to more than 30,000.

Those registered debris are the one big enough (of a size larger than about 10cm of cross section) to be tracked. In 2016, the ESA estimated that the number of debris in orbit was distributed as follows:¹⁴

- 34.000 objects greater than 10 cm,
- 900.000 objects from 1 cm to 10 cm,
- 128 million objects from 1 mm to 1 cm.

¹³The ESA reports the following: “There have been four confirmed collision events between catalogued objects so far. Moreover, there were several events reported as anomalies that resulted in several fragments observed on orbits close to the parent satellite in addition to a momentum change for the same satellite. It is likely that in such cases, the satellite suffered a space debris or micro-meteoroid impact.” (Accessible at the ESA’s website in their space environment statistics).

¹⁴These numbers were obtained by using the space debris environment model known as “MASTER”, for “Meteoroid and Space Debris Terrestrial Environment Reference”.

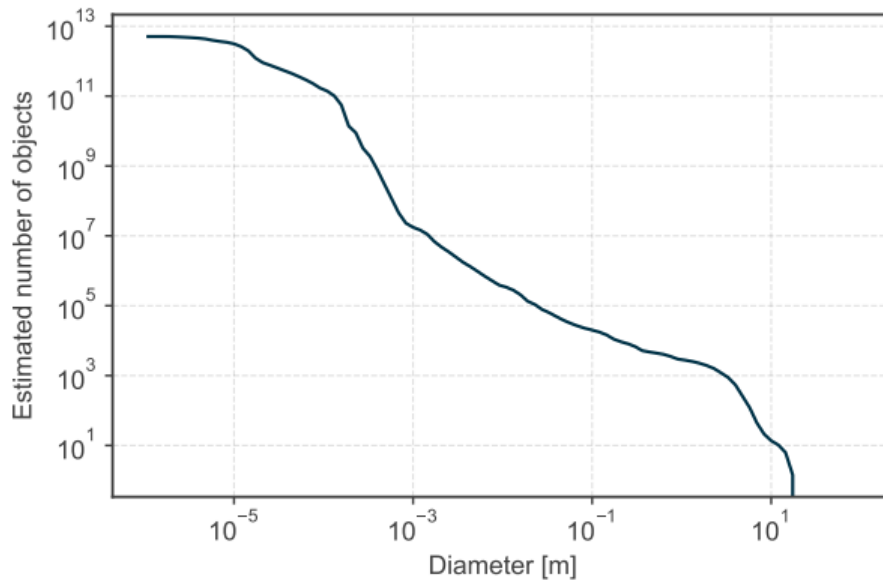


Figure 1.3: Estimated number of space debris objects as a function of the object size in Earth orbit. Source : ESA’s annual space environment report (2023).

Most of these objects are located in low Earth orbit. The distribution of the number of objects as a function of their size is shown in Figure 1.3. Bigger objects are more likely to disable a satellite. But they are also most likely to create new fragments of a big enough size to generate new fragments in turn.

Pardini and Anselmo (2021) provide an in-depth evaluation of the impact of space activities in low earth orbit. Figure 1.4, from their work, shows the repartition of the density of objects in low Earth orbit. “Catalogued” objects are the sum of densities of all objects. The largest densities are achieved around an altitude of 825 kilometres. At this altitude, most of the catalogued objects are fragment debris. At lower altitudes, from 225 to 625 kilometres, most of the catalogued objects are intact objects, spacecrafts and active satellites.

Figure 1.5 shows the density distribution of six clouds of debris coming from the main catastrophic fragmentation events.¹⁵ Debris from Cosmos 2251 and Iridium 33 are the consequence of an accidental collision between them. Debris from both Fengyun 1C and Cosmos 1408 are the consequence of two anti-satellite (ASAT) tests which were respectively carried out by China in 2007 and Russia in 2021.¹⁶ Debris from the satellite NOAA 16 and CZ-6A rocket body are the consequence of two accidental explosions. As shown in this figure, a few events are the cause of a large part of the debris density in some of the most polluted

¹⁵Catastrophic fragmentation events are intended (i.e. anti-satellite weapons) and unintended collisions or explosions that totally destroy a large object, thus causing to the creation of thousands of debris. Pardini and Anselmo (2014) does a review of past collisions examine the concept of catastrophic fragmentation.

¹⁶Bongers and Torres (2023) provide a review of the current trends in space weapons systems, their physical and economic outcomes, as well as a simulation of the long-run effects of a war in space.

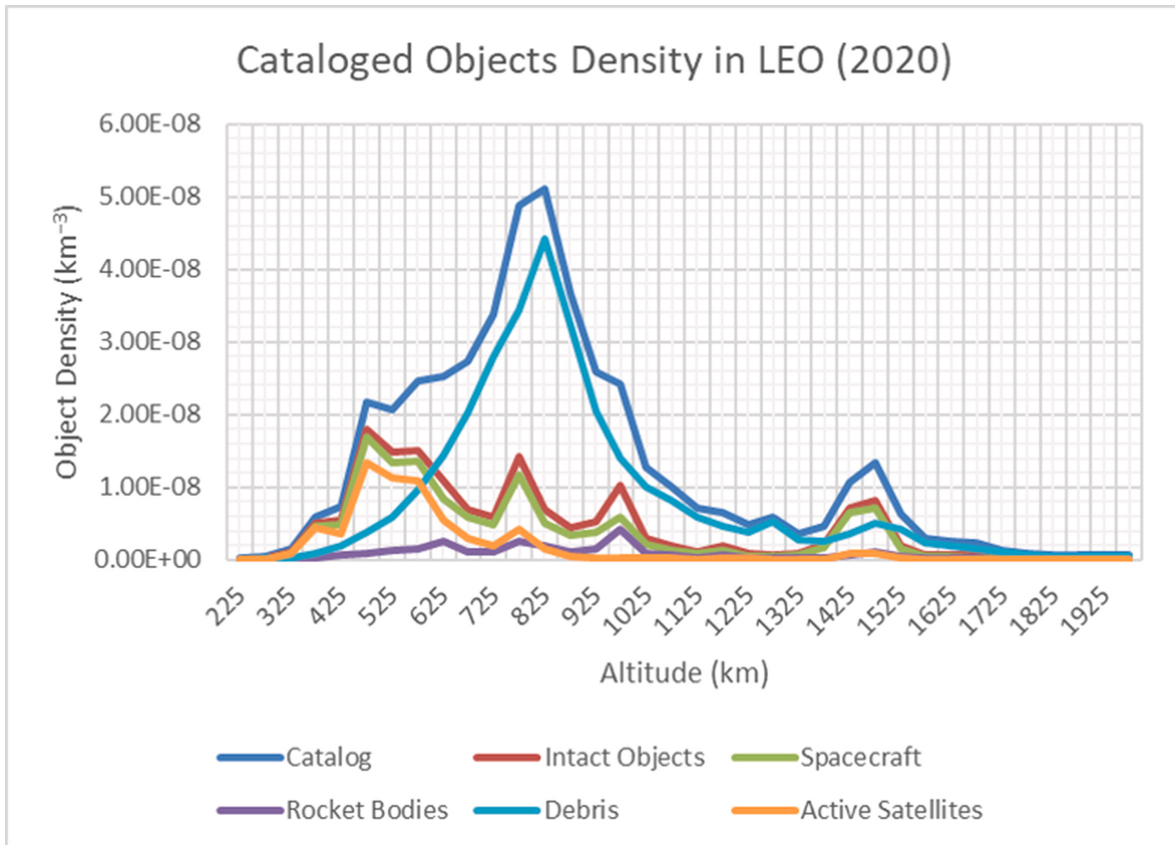


Figure 1.4: Distribution of all types of catalogued objects in LEO by altitude. Source : Pardini and Anselmo (2021).

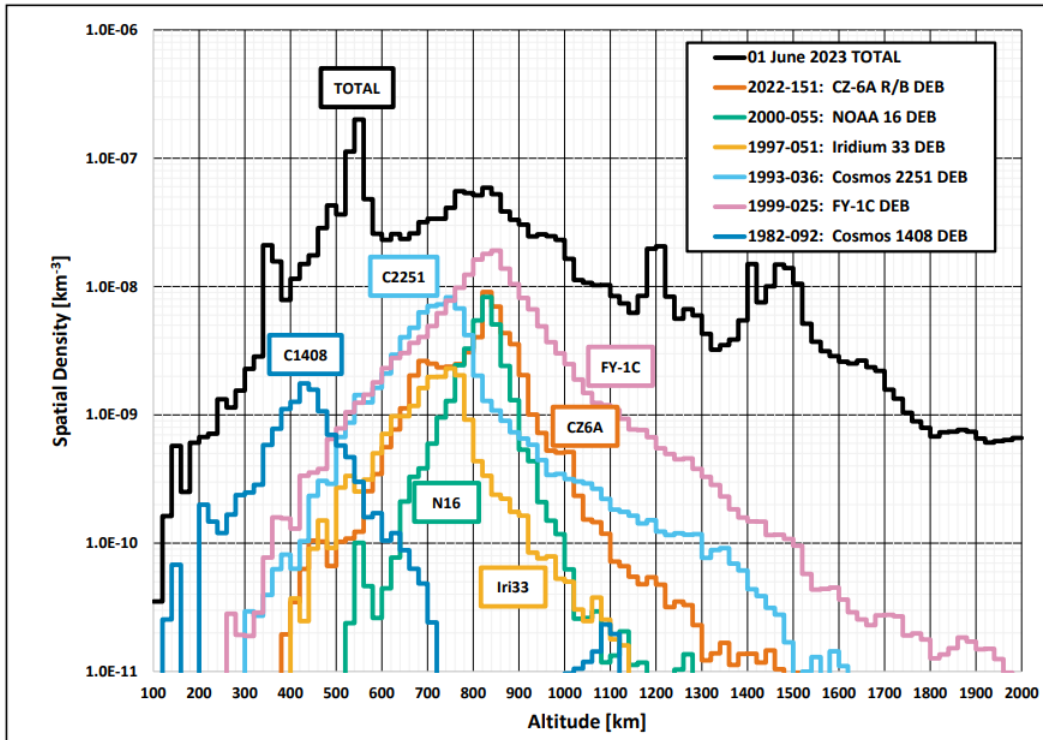


Figure 1.5: Total catalogued spatial density in LEO compared to the individual spatial density-altitude distributions of the six clouds examined. Source: Cowardin, H., *Orbital Debris Quarterly News* (NASA), Volume 27, Issue 3, August 2023.

altitudes. Some of these unique events could not happen again – anti-satellite tests could potentially not happen again. An increased emphasis on security could reduce or maintain a low rate of accidental explosions. But, as the number of debris grows, collision might become increasingly frequent. This is a result that can be observed in Figure 1.6, coming from an extrapolation made by the ESA. It shows that the cumulative number of catastrophic collisions in the next two centuries will continue to grow. This result is obtained either with a “business-as-usual scenario”¹⁷ (in red) and with a “no further launch scenario” (in dark blue).

1.3 Orbital management

The threat of an ever-increasing number of space collisions that would impair the development of space activities raises questions about the future of policy-making in this sector. This section aims to provide an introduction to the various aspects of Earth orbit management that will then be necessary to apprehend the review of the literature.

¹⁷A “business-as-usual scenario” reproduces the historical yearly launch rate in the coming years to evaluate the impact of an unchanged orbit-use effort.

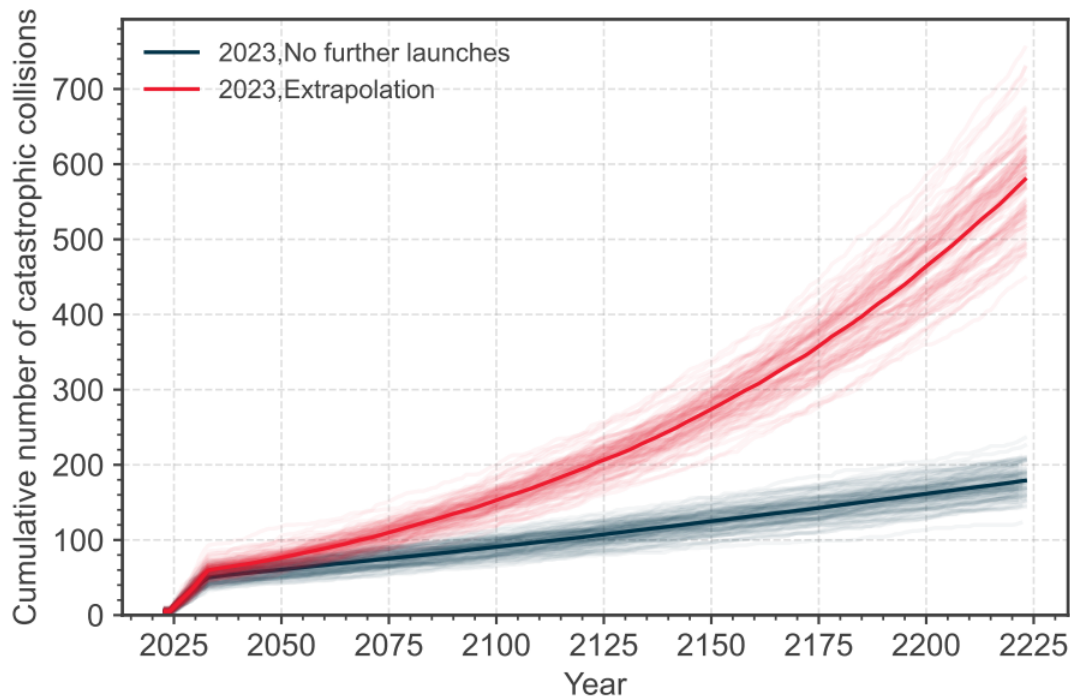


Figure 1.6: Extrapolation of the cumulative number of catastrophic collisions in both a “business-as-usual” scenario and the “no further launch” scenario. Source: ESA’s annual space environment report (2023).

1.3.1 The orbit, a common resource

Goods are often classified according to two properties. The first one is **excludability**. It refers to the ability to prevent an agent from consuming a good. This property determines whether or not it is possible to trade a good. If it is difficult or costly to prevent consumption, the good is considered to be non-exclusive. The second one is **rivalry**, or subtractibility of a good. A rival good is characterised by the fact that its consumption by one agent reduces the quantity available to others. Using these two properties, it is possible to categorise goods into four sub-categories.

Table 1.6 presents the different types of goods according to their access properties. The Earth’s orbit can be classified as a common good, or as a common resource. The exploitable orbital volume is finite, and certain altitude bands are more attractive than others. Any company therefore has potential access to the orbit, which makes it a non-exclusive good. But its use makes it a rival good: a large constellation, for example, can block access to an optimal altitude to another operator. In this case, it could be due to the impossibility of coordinating the satellites of two constellations so that they do not collide. In the longer term, orbit pollution must also be taken into account. By exploiting the orbit, satellite operators can make it unusable for others by creating too much space debris.

	Excludable	Non-Excludable
Rivalrous	Private goods	Common goods
Non-Rivalrous	Club goods	Public goods

Table 1.6: Types of goods

1.3.2 A possible fate of the orbit: The Kessler syndrome

An important characteristic of the space debris pollution is its self-growth. In 1978, Kessler and Cour-Palais predicted that collisions caused by small fragments (in opposition to collisions between intact objects) could become a major source of orbital collisions, eventually leading to an exponential increase of the flux of debris even in absence of new launches. After this publication, John Gabbard from the North American Aerospace Defense Command (NORAD) called this possible collisional cascading the “Kessler syndrome”. In the long run, it meant that the creation of fragments from collisions could become higher than other sources (i.e. natural meteoroids, launch-related fragments, and debris from accidental explosions). It was around this debate on the sustainability of orbital operations that a part of the literature first crystallised.

Over the years, multiple definitions have been associated with the Kessler syndrome. Kessler et al. (2010) note that not all of them are consistent with the original paper. Indeed, it has often been understood (e.g., by public media) as a situation that would worsen until a point where any newly launched satellite (or even rocket) would be destroyed almost instantaneously, rendering the Earth’s orbit de facto inoperable. Another version is a self-sustaining phenomenon, such that, even in the absence of human space activity, the number of debris would continue to grow because of collisions happening between themselves.¹⁸

Much more recently, Adilov, Alexander and Cunningham (2018) studied the possibility of such a situation. They then define the physical Kessler syndrome as a situation where “all functioning satellites will be hit during the period”, because the “collisional cascade renders an earth orbit unusable”. They have shown that an economic Kessler syndrome would occur before that. Whereas previous works modelled launches that did not depend on any economic variable, this new modelling takes into account the economic objective of satellite operators. The more the debris stock increases, the less profitable it is for space players to continue launching new satellites because of collisions. Their modelling showed that beyond a certain level of collision risk it would no longer be profitable to use the orbit.

The common good represented by the Earth’s orbit is therefore exposed to risks inherent to its governance. At present, there are no binding directives regulating the use of the orbit by the space industry. There are, however, recommendations (the main one will be discussed

¹⁸This mechanism where debris growth is self-reinforcing is also called “autocatalysis” in Rao and Rondina (2022).

in subsection 1.3.8), but there is no obligation to reduce, stabilise or avoid increasing current pollution. Satellite operators therefore have no incentive other than to increase their own current profits, and make no attempt to minimise the impact of their pollution on other current and future space players. The use made by one satellite operator thus is at the expense of others. By ignoring the external costs they impose on others, satellite operators collectively over-exploit their common resource. This situation, described by the ecologist Garrett Hardin in 1968, is known as the “tragedy of the commons”.

Not all who study common-pool resources accept Hardin’s framing of the likely “natural” trajectory of a common-pool resource and the necessity of centralised management, e.g. Ostrom (1990) illustrates how polycentric institutions (neither fully-centralised nor fully-decentralised) can evolve to sustainably manage a common-pool resource.¹⁹ However, both Hardin and Ostrom recognise that fully-decentralised management (i.e. open access) is not ideal for sustainability of common-pool resources.

1.3.3 The physics of the orbit

The following paragraphs summarise the main mechanisms at stake in orbit. These concepts will be used in the next subsection describing the dynamics of debris pollution.

Satellite launches are a primary driver of orbital population growth. Rockets carry satellite payloads into orbit, increasing the stock of operational satellites.

The jettisoning of rocket remnants (big debris). The upper stage of the rocket that inserts the satellite into orbit is left there, increasing the stock of big debris. Debris like this are big enough to be the source of a large number of debris fragments if a collision happens.

The unwanted creation of rocket by-products (fragment debris). The process of separating the rocket from the satellite during orbital insertion also produces some small fragments, e.g. bolts, paint flakes.

Debris decay. Uncontrolled objects (i.e. big debris) and fragments naturally “decay” from orbit as drag and gravity pull them back to Earth. Their rates of decay depend on their cross-sectional area and orbital altitude. Operational satellites in low Earth orbit expend fuel to maintain their orbits and counter atmospheric drag and Earth’s gravitational pull.

¹⁹Weeden and Chow (2012) study the applicability of Elinor Ostrom’s principles for sustainable governance of common pool resources to space. By applying these principles, the authors identified seven key considerations to manage the Earth’s orbit.

Satellites reaching their end-of-life. At the end of its active lifetime (e.g., because of a lack of fuel or because of an electrical/mechanical malfunction) a satellite which is not deorbited becomes an inactive object. End-of-life deorbit manoeuvres and active debris removal can also remove inactive objects from orbit.

Orbital collisions. Objects in orbit can collide, resulting in fragmentation. Collisions between debris are one of the main sources of new fragments. They can consist in collisions between small fragments and big debris (i.e. upper stage of a rocket or a satellite remnant) or between two big debris. Although another source of fragments, collisions between operational satellites and a big debris will be negligible in the long run if technological progress enables very low-cost object detection and successful avoidance manoeuvres.²⁰

1.3.4 The dynamics of space debris accumulation

A substantial literature has developed in aerospace engineering and related fields to explore the causes and consequences of space debris accumulation. This literature has developed physics-based models to predict the evolution of the debris stock in the coming decades and centuries.²¹ Some of them require to compute every object as distinct entities. Some others are simplified models (e.g., Farinella and Cordelli, 1991, Lafleur, 2011, Percy, 2015), where several object types are defined as homogenous populations.²² This last category is less computationally demanding and allows to study some general mechanisms at the core of the space debris issue. For these reasons, they are often used for economic applications.

Some of them are two-objects models (e.g., Farinella and Cordelli, 1991, Lafleur, 2011). They study the population of debris fragments on one side, and the population of intact objects (satellites) on the other. They are useful to study the evolution of the orbit from a physical point of view. However, they include all intact satellites in a single category, whether they are still operational or just the remnants of past operations.

²⁰Recent analysis estimates 86% of collisions occur between uncontrollable objects (Bonnal et al., 2020).

²¹Some examples are Cordelli et al. (1993), Liou et al. (2004), Drmola and Hubik (2018), Le May et al. (2018), Somma, Lewis and Colombo (2019) and Lucken and Giolito (2019).

²²Thanks to this simplification, these population can be modelled with a few differential equations.

Case illustration: A two-objects modelling.

Here is a simplified two-objects model of the evolution of the orbital environment. Consider the following dynamical system:

$$\begin{cases} \dot{x}(t) = \alpha q(t) - \underline{\beta}x(t) + \eta\theta x(t)y(t), & x(0) = x_0 \\ \dot{y}(t) = q(t) - \bar{\beta}y(t) - \theta x(t)y(t), & y(0) = y_0 \end{cases}$$

The first differential equation describes the evolution of the population of debris fragments, $x(t)$. The first term, $\alpha q(t)$, refers to fragments released as a by-product of satellite launches (i.e., explosion of rocket bodies and space objects), with $\alpha > 0$ their number per satellite launched $q(t)$. The second term, $\underline{\beta}x(t)$, represents the decay of debris fragments due to the atmospheric drag, with $\underline{\beta} > 0$ the inverse of their average orbital lifetime. The last term, $\eta\theta x(t)y(t)$, gives the addition of debris fragments generated by collisions of debris fragments with intact objects, with $\eta > 0$ their numbers per collision and $\theta x(t) \geq 0$ the rate of collision per satellite.

The second differential equation formalises the evolution of the population of intact satellites, $y(t)$. The first component, $q(t)$, is the result of the launch activity of the entire satellite industry. The second term, $\bar{\beta}y(t)$, refers to the decay of intact satellites, with $\bar{\beta} > 0$ the inverse of their natural average orbital lifetime. The last term, $\theta x(t)y(t)$ represents the number of collisions occurring between debris fragments and intact satellites.

Thereafter, the space activity is assumed to be constant, i.e. $q(t) = q$. It is also assumed that the orbital space starts unused (i.e., $x_0 = y_0 = 0$). The calibration of the two-objects model is presented in the following table:^a

Coefficient	α	$1/\underline{\beta}$	$1/\bar{\beta}$	η	θ	q
Value	70	1,000	10,000	5,000	4×10^{-10}	210
Units	frag./sat.	year	year	frag./sat.	1/year/sat.	sat./year

^aThe data is taken from Guyot and Rouillon (2023). Since it does not provide data for coefficient $\underline{\alpha}$, its value is taken from Farinella and Cordelli (1991) and Lafleur (2011).

Case illustration: A two-objects modelling - Results.

The following figures illustrate the results from year 1957 to year 8000:

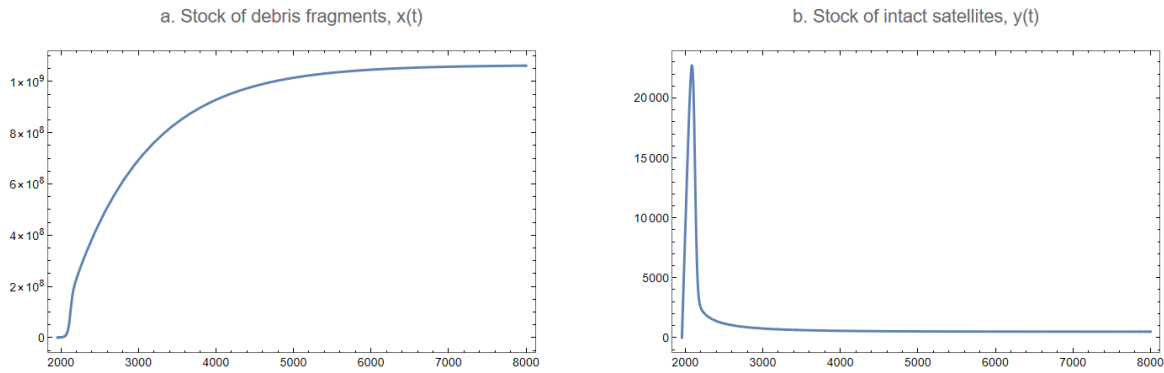


Figure (a) represents the dynamics of the debris fragment population x . Figure (b) represents the dynamics of the intact satellite population y . At each period t , the space industry launches a given number of satellites. At first, as the orbit is mostly clean, the stock of satellites builds up. Then, as debris fragments collide with them, the accumulation of new fragments increases at a growing rate. At some point, the number of collisions exceeds the launching rate, thus gradually reducing the satellite population. As the population of debris fragments keeps increasing, the expected orbital lifetime of a satellite decreases. Furthermore, as the stock of debris grows, the periodical flow of debris naturally decaying also increases. The gap between this negative flow of objects and the positive flow of additional satellites that transforms into debris fragments progressively vanishes. As a consequence, in the long run, the stock of debris tends toward an asymptote. Its value will depend on the physical characteristics of both the orbit and the satellites. This would result in a steady collision rate which in turn leads to a constant satellite fleet in orbit in the long run.

Two main shortcomings result from the absence of distinction between controlled and uncontrolled satellites. First, it is therefore impossible to model active satellites that can maintain their altitude on one side, and inactive satellites that fall back on the other. Second, collisions between inactive satellites cannot be modelled.²³ This does not allow to account for the shorter operational lifetime induced by collisions. This last point is a major limitation for economic models. The introduction of a third population can thus be required in order to study the economic incentives influencing satellites operators. For this reason, three-objects models are also considered. Rouillon (2020) uses a typology consisting of three populations: debris fragments, big debris (including inactive satellites and the rocket leftovers) and active satellites.

²³To model it, active satellites would have to collide with active and inactive satellites too. This would implicitly prevent to account for operational satellites' collision avoidance systems.

Case illustration: A three-objects modelling.

Here is a simplified three-objects model of the evolution of the orbital environment. Consider the following dynamical system:

$$\begin{cases} \dot{x}(t) = \alpha q(t) - \underline{\beta}x(t) + \eta\theta x(t)(y(t) + z(t)), & x(0) = x_0 \\ \dot{y}(t) = \lambda z(t) - \bar{\beta}y(t) - \theta x(t)y(t), & y(0) = y_0 \\ \dot{z}(t) = q(t) - (\lambda + \theta x(t))z(t), & z(0) = z_0 \end{cases}$$

The first differential equation describes the evolution of the population of debris fragments, $x(t)$. The first term, $\alpha q(t)$, refers to fragments released as a by-product of satellite launches (i.e., explosion of rocket bodies and space objects), with $\alpha > 0$ their number per satellite launched $q(t)$. The second term, $\underline{\beta}x(t)$, represents the decay of debris fragments due to the atmospheric drag, with $\underline{\beta} > 0$ the inverse of their average orbital lifetime. The last term, $\eta\theta x(t)(y(t) + z(t))$, gives the addition of debris fragments generated by collisions of debris fragments with intact objects, with $\eta > 0$ their numbers per collision and $\theta x(t) \geq 0$ the rate of collision per satellite.

The second differential equation formalizes the evolution of the population of rocket bodies and inactive satellites, $y(t)$. The first component, $\lambda z(t)$, represents operational satellites arriving at the end of their mission and becoming inactive, with $\lambda > 0$ the inverse of their average designed lifetime. The second term, $\bar{\beta}y(t)$, represents the decay of the stock of big objects due to the atmospheric drag, with $\bar{\beta} > 0$ the inverse of their natural average orbital lifetime. The last term, $\theta x(t)y(t)$, refers to inactive satellites destroyed by collisions.

The last differential equation gives the evolution of the population of operational satellites, $z(t)$. The first component, $q(t)$, is the result of the launch activity. The second term, $(\lambda + \theta x(t))z(t)$, refers to the number of satellites that cease to operate, either for technical (i.e., failures) or environmental reasons (i.e., collisions).

Case illustration: A three-objects modelling - Results.

Thereafter, the constant space activity is assumed to be constant, i.e. $q(t) = q$. It is still assumed that the orbital space starts unused (i.e., $x_0 = y_0 = z_0 = 0$). The calibration of this model involves a supplementary coefficient, λ (Guyot and Rouillon, 2023):

Coefficient	α	$1/\underline{\beta}$	$1/\overline{\beta}$	η	$1/\lambda$	θ	q
Value	70	1,000	10,000	5,000	4.65	4×10^{-10}	210
Units	frag./sat.	year	year	frag./sat.	year	1/year/sat.	sat./year

The following figures illustrate the results from year 1957 to year 8000:

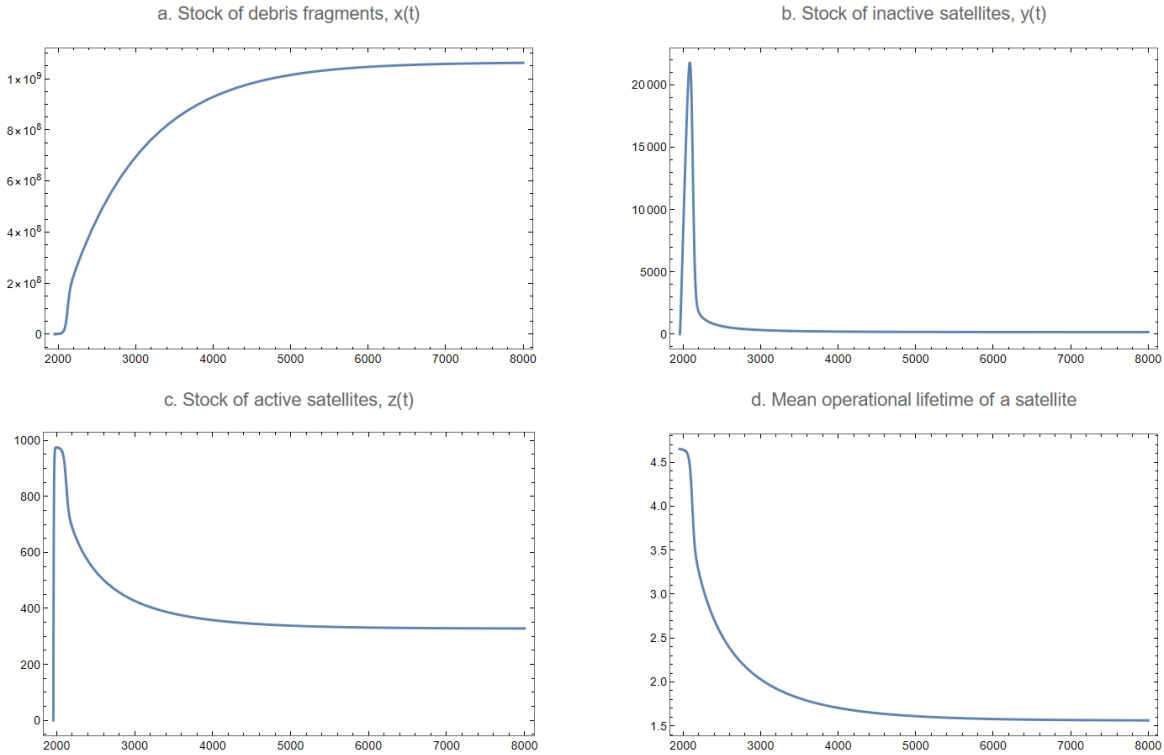


Figure (a) represents the dynamics of the debris fragment population x . Figure (b) represents the dynamics of the big debris (i.e. inactive satellites) population y . Figure (c) represents the dynamics of the operational (i.e. active) satellite population z . Figure (d) represents the dynamics of the mean operational lifetime of a satellite. At each period t , the space industry launches a given number of satellites. At first, as the orbit is mostly clean, the stock of operational satellites increases. This stock stabilises quickly at a level depending on both the launch rate and their mean operational lifetime. The mechanisms of debris accumulation are essentially the same than with a two-objects model. The stock of big debris increases, and then decreases as the stock of debris fragments increases the collision rate.^a Debris fragments grow asymptotically. Conversely, both the populations of big debris and operational satellites eventually decrease asymptotically.

^aThis illustrates a mechanism of the collisional cascading concept discussed in Kessler et al. (2010).

In the long run, both two-objects and three-objects models can lead to a “steady state”. Consider a situation where there is an exiting flow of debris fragments (because of the natural decay) that is proportional to the stock of debris fragments. The stock of debris fragments first increases as a result of launches and collisions. At first, the number of debris created is larger than the number of debris exiting the orbit. As the stock of debris fragments increases, so does the flow of exiting ones. The flow of exiting debris fragments would asymptotically tend to the flow of new ones. The long run state would thus consist in a situation where the stock of debris, active, and inactive satellites are steady.

Case illustration: A three-objects modelling - Steady state.

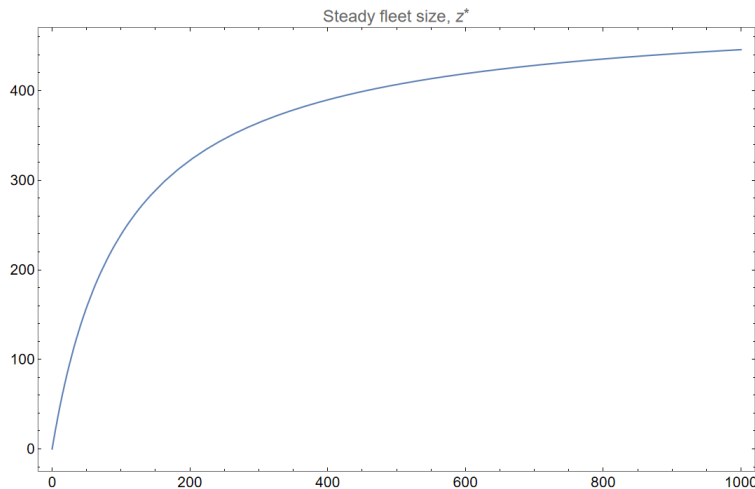
Here is presented the steady state resulting from a three-objects modelling. The steady state of the dynamical system, i.e., $x(t) = x^*$, $y(t) = y^*$ and $z(t) = z^*$ is defined as follows:

$$\dot{x}(t) = \alpha q - \underline{\beta}x^* + \eta\theta x^*(y^* + z^*) = 0,$$

$$\dot{y}(t) = \lambda z^* - \bar{\beta}y^* - \theta x^*y^* = 0,$$

$$\dot{z}(t) = q - (\lambda + \theta x^*)z^* = 0.$$

The following figure illustrate the long-run steady size of a satellite fleet z^* as a function of the launch rate q :



The fleet size grows as more satellites are launched annually, but collisions reduce the number of satellites which survive. As a result, the fleet size grows at a decreasing rate as the launch rate increases. Intuitively, higher launch rates imply larger fleet sizes. Larger fleets in turn imply more collisions and shorter expected lifetimes.

This illustrates the fact that a continuous orbital use, in the absence of a debris removal industry and all other things being equal, will create a pollution that would decrease the satellite fleet size in orbit for a given launching effort. The magnitude of the pollution created will vary with satellite characteristics. Some examples of these characteristics can be their sizes, affecting the number of debris that a catastrophic explosion would cause or their expected operational lifetimes, affecting their probability to suffer a collision. Two other major components are their altitudes and the implementation of post-mission disposal (PMD) measures. Post-mission disposal (i.e. end-of-life measures to take the satellite out of the protected orbit) compliance, if stringent enough, could greatly reduce the number of collisions. In addition, a lower altitude for satellite operations means a greater drag, and thus a greater natural cleaning. This will be discussed in more detail in section 1.3.8.

1.3.5 Orbit capacity: the question of sustainability

The future of Earth’s orbit will depend on how humanity will manage it. While orbital volume is a finite resource, satellite capacity (i.e., the number of satellites that the orbit could sustain) will vary with a number of parameters. The tendency for the amount of debris to increase until the orbit becomes unusable is not immutable. Firstly, because the orbit can be seen as a renewable resource. As shown in the previous subsection, in the long run, a constant launching policy may lead to a steady stock of debris. Indeed, debris in orbit (mainly in low-Earth orbit) gradually fall back towards Earth, either because friction with the residual atmosphere that gradually slows them down, or because of the thrust of solar radiation. This natural cleaning process can be accelerated by using on-board de-orbiting devices. It could also be supplemented by new debris removal technologies, for which the first prototypes are being tested and whose economic efficiency has yet to be determined.²⁴

Consequently, there are operating regimes that would enable to maintain the number of space debris at a fixed level, such that it would still be economically efficient to exploit the Earth’s orbit. In fact, the problem of space debris is similar to that of planetary limits discussed by Rockström et al. (2009). Like an ecosystem, the Earth’s orbit has the potential to absorb the pollution at a given rate, leaving humanity free to use it to improve its well-being. If too much debris is left in orbit, in the absence of strong enough mitigation measures given the number of satellites launched each year, the stock of debris fragments will rise again.

If it is possible to use the planet’s orbit in such a way that its capacity is not irretrievably degraded, it is therefore possible to implement sustainable exploitation policies.²⁵

The next subsections focus on the long-run sustainable orbit use management that can be characterised as the previously discussed “steady state”. The steady state describes a situation

²⁴Cleaner technologies will be discussed in section 1.3.8.

²⁵However, an important research issue concerns the path to reach this equilibrium. The work of Rao and Rondina (2022) consists in studying these dynamics.

where space activity-related choices (launches, debris removal, and satellite characteristics) and orbital populations (operational satellites, inactive objects, and fragments) are constant over time. The long-run satellite population (S) can then be expressed as a function of the long-run constant launch rate (Q) and a handful of technical and physical parameters. Again, the fleet size will depend on both the launch rate and the mean expected operational lifetime of a satellite. This approach focusing on the long-run steady state will serve to illustrate the mechanisms at stake when focusing on a sustainable state for the orbit.

1.3.6 Managing the orbit: the issue of economic efficiency.

Knowing what sustainable long-run steady state can be obtained from a given launch policy is a first step. Knowing what “should” be its level is another question, one of economic efficiency. This subsection gives an illustration of the allocation problem relating to orbit use, that consists in a trade-off between resources used to maintain the fleet to a given size on the one hand, and the welfare it provides on the other.

Consider the following situation. A satellite in orbit provides a service that is priced and sold at a value p . The revenue²⁶ of the satellite sector is thus equal to pS . All costs incurred to launch an additional satellite (i.e., to design, to manufacture, to insure,²⁷ and then to launch it) amount to a value of c . The private benefit of the fleet in orbit thus writes $pS - cQ$.

The social surplus measures the net benefit accruing to society from use of a resource, e.g. orbital space.²⁸ We assume that the price of a unit of service reflects the benefit to society provided by resource use, and that the cost of using the resource reflects the opportunity cost of diverting the necessary inputs from their next-best uses. In this situation, the social surplus of resource use is the difference between the total revenue generated by resource use and the total cost incurred, i.e. it is thus equal to the private benefit of the satellite sector.

Two regimes are a central focus in the growing economics literature on orbit use (e.g. Adilov, Alexander and Cunningham, 2015, Rao, Burgess and Kaffine, 2020, Rouillon, 2020). They are the key components to a valuation of economic efficiency.

The open access is a particular institution for managing a “common-pool resource”. It consists in the shared use of a resource in the complete absence of regulation. As of today, it can be understood as the “business-as-usual” scenario, as the present use of the orbit is mostly unregulated. Space powers do not enforce coercive rules, let alone to agree on a common set of regulations. It is often called a decentralised policy because of the absence of a governing head ruling for the best interest of the sector.

²⁶The word ‘revenue’ could be replaced, *mutatis mutandis*, with a more general term such as ‘benefit’ to reflect the value of the services supplied in the case of a civil government or military satellite operator.

²⁷Satellite insurance protects against physical loss, damage or failure. In 2018, 6% of satellites in LEO and 43% of satellites in GEO. They represented some \$5.5 and \$27.5 billion in insured in-orbit exposure (Undseth, Jolly and Olivari, 2021).

²⁸Social surplus is also referred to as the “rent” generated by the resource.

The social optimum is an orbit use pattern coordinated by institutions which maximises the social surplus from active satellites in orbit. As such, it is often called a centralised policy, as a single agent manages the access to the resource or because of a perfect coordination between several of them.

The economic efficiency can be defined relatively to the social optimum. A difference between an outcome and the social optimum is a loss caused by an inefficient resource allocation. An outcome which brings social surplus closer to its maximum level is thus said to “increase economic efficiency”.

The physico-economic equilibrium results from the private interests of actors interacting through this physical system. The orbit is shared between satellite operators that seek to maximise their own benefit. As such, they do not consider the negative external effect they have on others. The space debris pollution is the physical vector through which their competitors are affected. Each satellite operator maximises its own private benefit. As a result of this behaviour, they will launch satellites up to the point where launching an additional satellite would no longer provide a private benefit.

An open access physico-economic equilibrium is a special case of the physico-economic equilibrium in the absence of regulation. In this situation, as the private benefit is equal to the social one, this means that the social surplus from orbit use is dissipated.

A regulated physico-economic equilibrium is a physico-economic equilibrium that is “altered” by an economic regulation (e.g. a launch tax). By implementing such incentives, a centralised institution could bring the physico-economic equilibrium closer to the social optimum.

1.3.7 Regulating the orbit: The institutional management

The presence of an external cost in orbit conjugated with the uncooperative nature of a competitive market means that satellite operators will not be correctly incentivised to maximise the welfare from the orbit use. Their private interest leads them to

- not choose the most cost-efficient mix of technologies (i.e., by abstracting from the external benefit some of them may provide) or to not implement them,
- not finance the research and development of new clean technologies, and
- overuse the orbit, by launching too many satellites and/or by not deorbiting them quickly enough.

When faced with a pollution, there are several possible courses of action. The first ones

can be classified as command-and-control policies. Then, incentive-based policies will be presented.²⁹

1.3.7.1 Command-and-control policies

A command-and-control instrument directly prescribes modes of behaviour for a resource user to adopt, with penalties for non-compliance. It applies to situations where using some resource generates an amount of pollution. A command-and-control instrument could directly instruct resource users to use a specific technology (or set of technologies) to reduce their pollution production, or instruct them to reduce their resource use, or some other prescription. What distinguishes this approach from incentive-based policies is that users are given limited flexibility in choosing how they comply with the policy. Command-and-control policies can take the following forms:

The introduction of design and operating standards. Design standards can take many forms, such as the implementation or improvement of shielding, the use of better components to make satellites more durable or more efficient, or better collision avoidance capacities. Better operating standards consist to enforce behaviours that would lower unwanted consequences. Keeping enough fuel to be able to perform end-of-life manoeuvres is an example. In-orbit repair of satellite that suffered an unexpected failure is another one. It could also consist in choosing a larger security margin when considering a collision avoidance manoeuvre. Clean technologies will be discussed in section 1.3.8.

The implementation of a legal environment enabling the prosecution of polluters.³⁰ Many schemes could be imagined and implemented. A satellite left in a protected area of the orbit at the end of its lifetime could be fined.³¹ A system where a satellite operator whose satellite has been rendered inoperable could sue the operator of the satellite from which the debris fragment was created through a new dispute resolution court. A satellite operator could be fined for each creation of debris fragment that could be tracked back from one of its satellites that did not follow a given guideline. The possibilities would be numerous, but many would actually face severe limitations. One of the main ones is technical: as of today, only the largest objects can be tracked and attributed to a break-up event. If an approach focusing on sanctioning the damage caused is implemented, other problems would

²⁹The question of the plausibility of an internationally coordinated implementation of such policies is complex. Migaud (2020) reviews national and international treaties, and maps policy tools utilized by the United States to address the space debris issue. Percy and Landrum (2014) provides an overview of the current orbital debris regulatory structure of the United States. It also discusses the likeliness of adoption as well as the effects of several regulation scenarios.

³⁰Walmart, Zunnuraeni and Pitaloka (2023) analyse the implementation of the polluter pays principle applied to space debris.

³¹In 2023, a first fine for a satellite that failed to be placed farther enough from the geostationary orbit was issued (Euronews Green with AFP, 2023).

arise. Space debris being a cascading issue, many space operators could be responsible for the creation of a debris unit that would in time cause a new collision.³² The question of how responsibility should be shared is not a trivial one. Furthermore, firms are not infinitely-lived. As such, they could no longer exist long before the consequences of their inadequate behaviour.

A regulation by launch quotas at a yearly number chosen by a regulator. In the case of orbital pollution, however, this type of regulation is likely to have side effects. In fact, in response to this type of regulation, satellite operators would seek to maximise the service provided by the satellite. This new constraint could well have unintended negative consequences. For example, the satellites designed could be larger so as to carry more powerful systems, but potentially less efficient from an economic point of view. This new constraint means that the economically optimal design of a satellite, as targeted by a company maximising its profit, is no longer in line with its socially optimal design. Similarly, designing more massive satellites would lead directly to an increase in the stock of debris that could potentially be generated following a catastrophic collision, going against the original objective. Quotas based not on the number of launches, but on the mass put into orbit, would therefore seem more appropriate.

1.3.7.2 Incentive-based policies

An incentive-based (or market-based) policy alters a resource user's motivation to use the resource, usually with direct financial charges or payments making its exploitation more expensive. This gives the user flexibility to identify the lowest-cost methods available to them and leads to environmental improvement being produced at the lowest possible aggregate cost. Incentive-based policies are a central focus of the growing economics literature on orbit-use management, e.g. (Adilov, Alexander and Cunningham, 2015, Béal, Deschamps and Moulin, 2020, Rouillon, 2020), in part due to their popularity in economics more broadly (Blackman, Li and Liu, 2018, de Vries and Hanley, 2016, Kling, 1994, Stavins, 1998, Stavins, 2003).

A regulation by quotas of rights to pollute, which would relate to the creation of debris. Because of the specificities of space pollution, a version of a market of rights to pollute would be difficult to create. The ability to monitor debris creations is limited to large enough objects. All debris do not pose the same threat, depending on their orbital altitude, mass, size, inclination, etc., making it difficult to give a single "price" for a debris creation. Furthermore, the creation of debris fragments representing a threat to operational satellites can happen a long time after a satellite has been left in orbit. Nonetheless, a simpler version that would only target the satellites left into orbit after a defined number of years could be implemented. Guidelines concerning the maximum time that a satellite should spend in orbit

³²Space debris can be understood as a nonpoint pollution. For Segerson (1988), some of such situations can be challenging to monitor, as "the actions of several polluters contribute to the ambient levels and only combined effects are observable".

after the end of its operations already exist, but are not mandatory.³³ Such a scheme could force satellite operators to not exceed a given percentage of satellites that would not comply with these guidelines.³⁴ It could also take the form of a deposit-refund scheme. Satellite operators could pay a deposit before launching a satellite then get a refund if it complies with the standard at the end of its lifetime.

A market of tradable launch permits which would consist in limiting the number of annual launches in order to reduce the risk of collision in the longer term. Only a given number of launch permits would be emitted each year. These permits could then be traded on a dedicated market, as in the case of the European carbon market (Emissions Trading Scheme, ETS). Such a market solution is often considered in environmental economics.³⁵

The introduction of taxes. Consider a tax³⁶ on satellites launching, or a fee periodically paid for each satellite (active and inactive) in orbit.³⁷ By increasing the cost paid by satellite operators, these economic instruments could disincentivise orbit use, ultimately leading to less debris emissions. A launch tax directly and uniquely decreases the incentive to launch a satellite. However, for the same reason as discussed about the launch quotas, taxes should focus on the mass sent in orbit. A satellite tax not only disincentivises the launch of satellites, but also the total time they will spend in orbit. This may incite satellite operators to reduce the time spent in orbit after a satellite becomes unproductive, and thus the time during which a satellite could suffer a collision.

The introduction of a clean-up market, which could consist of an obligation to purchase rights before launching a new satellite. This mechanism would serve to fund a debris removal service. A regulator would use the fund to finance the most cost-efficient proposals. This mixed solution is often explored in the literature as it allows to quantify the potential demand for such a cleaning technology.

1.3.7.3 Compared outcomes and limits

Economic incentives are usually regarded as more efficient than command-and-control

³³See the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines.

³⁴This given percentage could be allowed at altitudes where satellites cannot naturally fallback to Earth in a short enough time. As they could need the help of their propulsive device to comply with the duration guideline, a small percentage of failures, caused by defective component, could be tolerated.

³⁵ Ellerman and Joskow (2008) provides an overview of the European Union's Emissions Trading System. A recent paper from Bayer and Aklin (2020) showed that this market has been effective to reduce greenhouse gas emissions even in spite of low prices.

³⁶This tax, as a Pigouvian one, is meant to price negative external effects (Sandmo, 1975).

³⁷Here, we consider taxes that are not directly linked to debris creations, because of the previously discussed limitations concerning their monitoring and dilution of responsibility through the cascading effect and the time that can pass between the launch and the destruction of a satellite. For these reasons, we do not consider an affluent tax, but a more general Pigouvian tax, defined as follows: A tax on an economic agent who creates adverse side effects for society, that is intended to incentivise him to reduce this pollution.

policies. Requate (2005) discusses the effects of environmental policy instruments on both adoption and development of advanced abatement technology. It concludes from the literature that under competitive conditions market-based instruments usually perform better than command-and-control. Performance standards stand between technological standards (command-and-control) and market-based policies. Performance standards usually consist in forcing industry firms to not exceed a given level of emissions. Otherwise, they can be fined or forced to terminate their activities. Bergquist et al. (2013) gives a literature review of both the theoretical and empirical conditions under which performance standards can provide efficient incentives for emission reductions and abatement technology adoption. However, Cole and Grossman (1999) does a literature review of the empirical literature and argue that command-and-control is not invariably less efficient than economic incentives.

To give an illustration of the efficiency of economic incentives, consider a polluting industry. The regulator has two possibilities. The first one is to enforce a new technological standard that the industry has to implement. If the technology is adopted, pollutant emissions will decrease of a given percentage per unit produced. The second possibility is to set a tax or another economic incentive aiming to change the behaviour of the firms. They will try to minimise the addition of both the cost of their emissions and the cost of the abatement technologies (i.e. cleaner technologies) they will choose. In this situation, firms will:

- Choose the mix of technologies that will be the most economically efficient. If the externalities are internalised, the outcome of this policy will also be an allocation that will be the most efficient, resources and pollutedly-wise. Depending on both the availability of other technologies and on the tax level, firms could thus potentially adopt technologies that could have a greater effect on decreasing the emissions.
- Firms will also be incentivised to fund the research and development of more efficient technologies.

Furthermore, the total cost of a given level of environmental improvement will generally be higher under a command-and-control policy than if it were achieved through an incentive-based policy (e.g. see the discussion on page 686 of Cropper and Oates (1992)).

Experience in other resource contexts tends to confirm that command-and-control policies often result in further responses by resource users which may undermine the overall goal of the policy. In fisheries, attempts to preserve fish populations by restricting the number of boats in the fishery led to “capital stuffing”, where existing vessels invested heavily in increasing their harvest capacity (Townsend, 1985). This can be compared to the issue of taxing a satellite rather than its mass, as discussed above. Similarly, attempts to preserve fish populations by limiting the total amount which could be harvested led to the “race to

fish” phenomenon, where fishers sought to harvest as much as possible before the catch limit was reached (Birkenbach, Kaczan and Smith, 2017). By contrast, incentive-based policies such as individual tradable quotas directly target the incentive to use the resource and thus avoid such “perverse” effects (Costello, Gaines and Lynham, 2008).³⁸

The satellite industry faces another challenge. Consider a cleaner technology that would reduce the pollution per satellite launched. The orbit is under open access. To keep the example simple, consider that the cost of this new technology is negligible, and that the entire industry thus adopts it. In the short-run, the external cost would decrease, thus increasing the profits of the firms. As a result, they would eventually increase their launch rate. In the long run, satellite operators will launch more satellites, increasing the collision rate until the expected profit of a satellite is equal to zero again. This mechanism is also known as the Jevons’ paradox.³⁹ Such a situation demonstrates the need for a regulated orbit to accompany the implementation of cleaner technologies in order to optimally manage the orbit.

1.3.8 Regulating the orbit: The need for clean technologies

As previously discussed, an institutional management can both affect the orbit use (i.e. by altering the incentive to launch and to leave a satellite in orbit) but also incentivise to adopt and research new technologies. New technologies also enable new operating standards. This subsection aims to provide an overview of these technologies. Space activity and the orbital environment are influenced by technologies which reduce the environmental footprint of orbit use. Cleaner technologies reduce the external cost for a given level of orbit use. Their implementation could thus increase the efficiency of the satellite industry. Technological approaches to managing orbit use can be classified according to whether they target launch vehicles, satellites, or debris.

1.3.8.1 Cleaner launch technologies

Clean orbit-use technologies focused on launch vehicles aim to reduce the amount of debris produced when delivering a payload to orbit. They can focus on the rocket body (e.g. boosters to deorbit the upper stage) or on the small debris fragments released (e.g. frangibolts to separate payloads).

³⁸More technically, command-and-control policies can be expressed as an implicit price reflecting forgone profits due to an economically-binding constraint. The policy thus changes the relative prices of using a resource or deploying a particular set of technologies. Incentive-based policies can also be expressed as taxes which change relative prices. However, because command-and-control policies do not directly alter the resource users’ objective functions, operators remain interested and able to seek ways to mitigate the effects of the implicit price change. Incentive-based policies do not face this problem because they directly target the users’ incentives to produce socially-undesirable outcomes.

³⁹See Alcott (2005) and Gillingham, Rapson and Wagner (2016) for a better understanding of this paradox.

1.3.8.2 Cleaner satellite design technologies

Clean orbit-use technologies focused on satellite design can be classified into three categories: “reliability” technologies which extend a satellite’s operational life; “end-of-life disposal” technologies which enable satellites to be deorbited (or reorbited to a disposal orbit) at the end of their productive life; and “shielding” technologies which improve a satellite’s resistance to collisions. Saleh, Hastings and Newman (2002) discuss various issues driving and limiting spacecraft design lifetime, and develop an economic metric (“cost per operational day”) to help guide the necessary design specifications. Davis, Mayberry and Penn (2019) extend this analysis by considering on-orbit servicing technologies, i.e. satellites which can repair and refuel other satellites. Such technologies would likely affect the average operational lifetime of a satellite. Sánchez-Arriaga, Sanmartín and Lorenzini (2017) compare several end-of-life disposal technologies, finding that bare electrodynamic tethers may dominate other deorbiting technologies in terms of performance and reliability.⁴⁰ Wiedemann et al. (2008) model the cost of better satellite shielding to reduce damages from hypervelocity impacts. Results show that simple modifications of satellite walls can reduce failure rates by up to 1%, i.e., enough to be cost-effective if the shielding is not too expensive.

1.3.8.3 Debris removal technologies

Active debris removal (ADR) involves technologies that can capture and deorbit debris. They may differ depending on whether large intact objects or small fragments are targeted. The former will be referred as “intact ADR” and the latter as “fragment ADR”. Intact ADR technologies typically involve “rendezvous and proximity operations”, where the object to be deorbited is targeted and located in advance. By contrast, “collection/pickup” technologies remove all objects of a given type within a target region, and are better suited to fragment ADR.

While there are a number of companies planning to offer intact ADR services in the near future, it is unclear when or how fragment ADR will be offered commercially (Weinzierl, 2018). Mark and Kamath (2019) review the technological challenges and conclude that all plausible ADR systems are still in experimental or conceptual stages and require more study before they can be deployed at scale. Weeden (2011) analyses the legal and policy issues facing ADR deployment and concludes that there are substantial non-technical barriers before ADR services can be deployed at scale. Still, Muller, Rozanova and Urdanoz (2017) as well as Brettle et al. (2019) demonstrate the value of ADR for space actors. Furthermore, Adilov, Alexander and Cunningham (2020) demonstrate that ADR may be necessary in order to halt orbital debris accumulation. Richardson and Hardy (2018) claim the reusable launch vehicles could lessen the cost of ADR from 2.8% to 21.7%, depending on both the

⁴⁰A bare electrodynamic tether is a thin unshielded length of conducting wire which generates electric potential through interaction with the Earth’s magnetic field. This electric potential is then converted to kinetic energy, facilitating the deorbit process.

technological attainment and the competitiveness level in this market. Finally, Klima et al. (2018) show that leaving ADR decisions to individual space actors can result in inefficient and inequitable outcomes.

1.3.8.4 Cleaner end-of-life technologies and associated standards

End-of-life requirements are an example of a command-and-control policy: a binding requirement to deorbit a satellite upon the end of its mission. This command-and-control is frequently discussed in the literature about space debris. The current 25-year deorbit guideline at the international level is a step in this direction, though it is both legally and economically non-binding.⁴¹ At the national level, the US Federal Communications Commission recently implemented a 5-year deorbit requirement as a condition for satellite licensing – a true command-and-control policy (FCC, 2022). There are three ways a satellite can comply with deorbit requirements: through choice of altitude, through use of technologies (e.g. boosters), and through a mix of both.

The first approach relies on the fact that some regions will be naturally compliant with a given deorbit requirement, i.e. satellites left there will deorbit within the required timeline without any intervention. By choosing a suitable operational altitude, an operator can ensure that their satellite complies with the requirement without any additional end-of-life effort. The second approach relies on technologies which enable a satellite to actively deorbit at the end of its life. With such technologies available, an operator need not place their satellite in a naturally-compliant region. The third approach is to move intact inactive payloads from higher to lower altitudes where they will be naturally compliant with the requirement without further operator effort. This third approach is only feasible in LEO, as in GEO the corresponding requirement would involve reorbiting to a higher (“graveyard”) orbit, i.e. moving the satellite out of the way without disposing of it.

Rao and Letizia (2021) consider the short-run physico-economic effects of full compliance with the 25-year guideline in LEO. They find that operators using this approach will increase the expected collision rate at the naturally-compliant altitudes, inducing operators to cluster at nearby higher altitudes. This clustering may create greater collision risks there if collision avoidance manoeuvring is imperfect. Engineering studies have also indicated that the 25-year guideline is insufficient to prevent further growth of debris fragments and collision risk even with perfect compliance and no clustering effects, necessitating a “more stringent” (shorter) post-mission disposal (PMD) timeline (Virgili et al., 2016; Lewis, 2020). There is as yet no research on the long-run physico-economic effects of either more-stringent timelines or binding deorbit requirements.

⁴¹Percy and Landrum (2014) studies the effect of non-binding debris mitigation guidelines in the US on satellite operator behaviours. They find that non-binding guidelines tend to have low compliance relative to those which bind, and consider a suite of options for implementing binding disposal requirements. The “Unilateral Regulation Overhaul” option they describe can encompass both incentive-based and command-and-control policies.

1.4 Literature review

1.4.1 Formal models

Formal models that can be analytically solved are used to get a grip on some physical and economic mechanisms. Their structure allows to derive proofs and theoretical results that enhance the understanding of the system it describes. This enables a better understanding of the consequences of human activities and how to regulate them. By aiming for a sustainable and efficient orbital use, these models help to guide the policymakers on how to increase the social well-being. These works are often completed with numerical simulations that illustrate the theoretical results.

Physical models often reproduce the launch rate of the past (e.g. Rossi et al., 1998, Dolado-Perez, Revelin and Di-Costanzo, 2015, Wang and Liu, 2019), scenarios considering increased launch rates compared to the past (e.g. Öz, 2021) or including the launch rate needed for the creation of new constellations (e.g. Lucken and Giolito, 2019). The reason behind these modelling choices is that the future of orbit-use will depend on a lot of uncertainties. Technological advancements, such as a decreased launch costs or decreased satellite production costs are one of the main drivers of the demand. Innovations can also create new services or increase the competitiveness of orbital solutions. The economic climate also plays a role in the investment in the space industry. However, exploring the incentives of orbit-use with the help of economic models exploring the behaviours of satellite operators is key to guide future policies. These models aim to analyse how the firms will respond when placed in a given situation. By doing so, it becomes possible to understand how the future of space environment will affect the satellite industry and to explore the efficiency of a given regulation set. To the best of the author’s knowledge, the work of Adilov, Alexander and Cunningham (2015) was the first to include an economic analysis of satellite operators behaviour.

Adilov, Alexander and Cunningham (2015) proceeded as follows. They use a two-period model of Earth orbit, where a product differentiation is modelled using a Salop circle where satellites are located.⁴² All satellites are substitutable, but consumers prefer satellites near them. During the first period, firms choose to (or not to) launch a satellite. Launching a satellite is accompanied by the creation of debris generated by launch vehicles. Firms can choose between different level of mitigation technologies to reduce the number of debris generated. At the end of this period, a fraction of the satellites is destroyed by colliding with these debris. The second period only consists in the collection of revenues from the remaining satellites in orbit. On the one hand, as the stock of debris decreases the probability that a satellite is still operational at the start of the second period, the expected revenue of a firm decreases with an increased use of the orbit. On the other hand, the destruction of satellites decreases the supply, and thus increases the expected revenue. Satellite operators

⁴²Salop (1979), the eponym author, modelled a problem of spatial competition through a circular market.

anticipate this outcome, and adapt their launch rate to orbital congestion. The authors compare a decentralised scenario with an optimal situation where a social planner internalises the externality caused by debris. They show that the decentralised situation is the less socially desirable, as firms will always choose the cheapest and thus less efficient mitigation technologies and launch too many satellites. They also demonstrate the efficiency of a Pigouvian tax.

This model, because of its assumptions, described a very specific structure of a satellite industry. By assuming that the differentiation of satellites comes from its constant proximity to a customer, it implicitly assumes that a satellite is constantly over the same Earth location. This modelling thus specifically fits the geostationary orbit, where several operators can compete for servicing some geographical areas. However, the issue of space debris is particularly critical for low Earth orbit. For this reason, a range of more general models have been developed to analyse the economics of orbital management.

Adilov, Alexander and Cunningham (2018) then proposes a simplified dynamic model of the orbit. Contrary to the preceding work, satellite operators can choose their launch rate at each period and will adjust it in reaction to environmental changes. Two types of objects are considered: satellites and debris. Launching satellites creates debris causing a risk of destructive collisions. The last source of debris are collisions between active satellites and debris. At the end of their lifetime, satellites are instantly disposed of. A perfectly competitive market is assumed. The price decreases with the number of satellites available. Satellite operators thus launch satellites as long as the expected revenue of a satellite is higher than its cost. As time passes, the stock of debris grows, thus decreasing the productive lifetime of a satellite. The introduction of such an economic incentive allows them to show that an “economic Kessler syndrome” would precede a “physical Kessler syndrome”, i.e., that it would become too costly to launch a satellite long before there are enough debris to destroy every satellite in orbit during a single period.

This kind of modelling abstracts from an important mechanism of space debris accumulation. Indeed, the stock of debris fragments builds-up, but there is no growing population of unmanned large objects threatening to suffer new catastrophic collisions. The moment humanity would stop its spatial activities, the orbital environment would start to clean itself. Two ways are often used to deal with this issue. The first one is to account for a third population type that consists of large uncontrolled objects. The second one is to consider every debris as a potential source of more debris fragments, as the design of the following paper illustrates.

Bongers and Torres (2023) propose a dynamic investment model. Satellites collide with debris created by space activities. Satellites operators are profit maximizing entities that disregard the social cost of pollution. They also use a two-objects model. In contrast to Adilov (2018), a portion of satellites are transformed into a single debris each at the end of their

lifetime, and collisions can happen between debris themselves. This last component means that a cascading effect of never-ending collisions can happen. It is assumed that the market is perfectly competitive. Diminishing returns for satellite services are postulated, leading to a decreasing inverse demand. The outcomes of two scenarios are compared: with and without debris creation. In the latter case, satellite operators include the risk of destruction of their satellites in their profit maximisation decisions. Their simulations show that, even without further cost reductions, the stock of debris will increase before stabilizing. This model allows to derive an expression for the maximum number of satellites to prevent the (physical) Kessler syndrome. This new modelling confirms that the economic Kessler threshold is lower than the physical Kessler threshold.

Such modelling allows to account for a debris growth that is not only linear with the launch choice made by satellite operators at a given moment, but also with past choices, as debris previously created will generate more debris later. The following paper models debris-debris collisions, and also adds collision between satellites.

Rao and Rondina's (2022) work is based on a dynamic model where satellites keep being functional until being destroyed in a collision. Satellites can collide with debris and with themselves. Debris can also collide with themselves, a mechanism that they call "autocatalytic growth". In their simulations, imperfect collision avoidance can be accounted for. They compare the open access management to the optimum where external costs are internalised. They show that the occurrence of a Kessler syndrome necessitates debris-debris collisions, and that it is a possible outcome even if satellite operators respond to congestion by lowering their launch rates. They also demonstrate that thanks to the orbital decay acting as a natural cleanup, it is possible to reach a steady state that would not consist in a Kessler syndrome equilibrium. A Kessler syndrome is more likely as the rate of return of satellites increases. They also confirm that open access lead firms to launch too many satellites compared to the optimum.

Debris-debris collisions allows to account for a delayed effect of space activity, but modelling it through a single population forces to abstract from another mechanism. Over time, a debris that is the consequence of many collisions must have become smaller and smaller, up to a point where it is too small to both threaten active satellites and to threaten large object of catastrophic collisions. The mass of matter sent in space matters, meaning that a finite volume should not be able to generate an infinite number of harmful debris fragments. This is especially important in the long-run, where the environment is theoretically the result of an infinity of interaction between objects. For this reason, using three populations to model the long-run might be valuable realistically-wise. By doing so, large objects (i.e., active and inactive satellites, rockets upper-stage) become a limited "potential source"⁴³ of debris fragments depending on their average mass and volume. This could also be achieved through the

⁴³Some large objects might fall back to Earth before experiencing a fragmentating collision.

use of two populations of both large objects and small fragments. However, differentiating operational satellites from other large objects might be crucial for an economic analysis, as the expected profit from a satellite operator directly depends on the expected lifetime of its assets. This explains the modelling choices of the following work.

Rouillon (2020) develops a new physico-economic model of the orbit inspired by bioeconomics. Its physical model is based on modelling the evolution of three populations of distinct objects: the satellites and the inactive satellites that might be the source of future fragments, and the debris fragments threatening satellites of destructive collisions. The lifetime of a satellite depends on two elements. First, its conception choices that set its failure rate. A failed satellite becomes an inactive satellite. Second, the environment on which depends the rate of collision. A formal solution of the long-run equilibrium can be derived from any given launch rate. A higher launch rate reduces the expected lifetime of a satellite. This affects the profits of satellite operators. Using this model, it becomes possible to express the maximal carrying capacity of the orbit. The “open access” scenario within perfect competition is compared to the optimal (centralised) scenario. The results show that open access always lead to overuse the orbit, but also demonstrates that a launch tax would be able to efficiently regulate the satellite sector.

Béal, Deschamps and Moulin (2020) focuses on the way to manage the orbit through several management conditions, while also considering the funding of a hypothetical debris removal industry. It considers a competitive market where firms decide how many satellites they launch. The revenue of a satellite is normalised to one, such that the profit of a satellites fleet depends on the ratio between the revenue and the cost to deploy the fleet. They consider decreasing returns for new satellites, i.e., the marginal satellite cost of a satellite operator increases with its fleet size. A static model of orbital congestion is built around these assumptions. Satellites collide with each other, determining the probability of failure of a satellite knowing the total size of the fleet in orbit. They compare three situations: an unregulated one, another one where launches are regulated by a central agency, and a last one where the central agency would only set a launch tax. The launch tax would finance cleanup technologies that would reduce the collision rate. They find that it is twice as easy to recover cleanup costs with the centralised planner than in the unregulated situation. This result incentivises the implementation of a centralised solution. They also show that a linear tax is two times as effective as a quadratic one.

The previously discussed papers assumed that a large number of satellite operators competes for the orbit. The rise of some new large constellations in low Earth orbit led to consider the consequences of an oligopolistic use of an orbital region.

Bernhard, Deschamps and Zaccour (2023) model the strategic interactions of two satellite mega constellations. The operational life of a satellite ends when a satellite quits the constellation. This can happen because of natural decay, component failure, or consequently to a

collision. Similarly to Rao and Rondina (2022), collisions can happen between both satellites and debris and between debris themselves. Satellites within a fleet are coordinated in such a way that they cannot collide. Collisions between both fleets of satellites are assumed to be avoided through just-in-time collision avoidance manoeuvres. Each firm performs the manoeuvre half of the time. These manoeuvres reduce the orbit time of a satellite, by expending propellant. This externality of space congestion is priced through as an operating (i.e. yearly) cost. The additional revenue of a marginal satellite decreases with the size of the fleet. Both a linear and a concave revenue functions are tested. The services provided by both firms are in competition, depicting a dynamical duopoly. Both satellite operators compete for the use of an orbit area through the channel of space congestion. Firms maximise their profits by solving an infinite-horizon dynamic optimisation problem. The stock of debris is sought to be kept constant at its initial value, following an international agreement. This means that in order to maintain a fleet of satellites, active debris removals must be financed. A supra-national agency charges the firms with the cost of removing the debris created each year. The taxation depends on the share of the debris creations that can be attributed to the satellite operator. The cooperative optimum is compared to the noncooperative Nash equilibrium. They show that competition increases congestion and its associated cost, but the difference between these alternatives may be small. They also demonstrate that a launch tax could finance the cleanup of space debris if its cost is low enough. Otherwise, they should be taxed according to the amount of debris they produce.

Faced with the congestion problem of the orbits, it is important to understand how some incentives can influence the behaviour of satellite operators. Taxing the use of space is not the only incentive that might be necessary to optimally manage the low Earth orbit. Cleaner technologies and operation standards play an important role in the efficient use of the Earth orbit. The next paper covers the question of how to incentivise private operators to correctly invest in both.

Grzelka and Wagner (2019) propose a static model with perfect competition. The revenue for the satellite service is given. A representative firm chooses the values of two input variables, so as to maximise its profit. The first is an ex ante policy, in the form of a range of satellite design choices (i.e. shielding, manoeuvring ability, collision threat detection and avoidance capabilities). The second is an ex post one, also known as a take-back program.⁴⁴ Private satellite operators have an incentive to use both ex ante and ex post policies to reduce the probability than their satellites are destroyed. However, there is no incentive to reduce their impact on others. For this reason, they underinvest in both sectors. Contrary to previous papers that focus on how to correctly price the external cost of orbit-use, this work

⁴⁴

A system of monetary reward granted for returning (i.e. satellite atmosphere re-entry) or secure (i.e. by sending it to a graveyard orbit) spent satellites and generated debris.

focus on how to correctly price the external benefit of cleaner behaviours. They propose that the direct way would be to implement a “Pigouvian subsidy”, such that the external benefit is paid to the private firm. However, the authors argue that it may not be politically feasible. In reaction, Grzelka and Wagner (2019) discuss several regulatory options to cope with orbital pollution. First, they propose that policymakers should strengthen and clarify intellectual property rights as a mean to boost the incentives of firms to innovate. The possibility to monetise some innovations would increase the value of the research and development effort in cleaner technologies, thus inducing higher quality satellites while reducing their debris emissions. On the side of the take-back programs, NGOs and governments should have two roles: promoting take-back initiatives with studies showing that private benefits would be higher if they collectively run those programs, and a Coasian role that would consist of lowering transaction costs of cooperation.

Macauley (2015) proposes a model based on two time periods of 20 years each. It is implicitly assumed that the market of satellite operators is competitive. Between two periods, the stock of debris increases by two mechanisms. Already present debris increases by a given coefficient because of collisions between themselves. New debris are also added proportionally to the launch rate. Its analytical approach relies on an assessment of the externalities generated by the launch of a satellite, so that the corrective effects of three approaches can then be measured. The first is a tax on launches only. The second one is a tax followed by an ex post rebate if a successful graveyarding of the spacecraft is enforced correctly. The last one is the same principle, applied to the implementation of avoidance measures. The results shows that the most effective type of instrument is the ex post rebate. Indeed, this kind of approach allows to monitor the results of firms’ choices, thus enabling to correctly incentivise them.

1.4.2 Empirical and computational models

Because of the complexity of the orbit physics, computational models allow to increase the precision of the calculated results. For example, whereas a model that can be solved analytically will use populations, computer models can simulate each individual one by one. Empirical studies about the orbit and the satellite industry uses the current state of the environment to generate new data usable to guide new research and policies. This subsection focuses on the results obtain by such methods.

Other models usually focus on the future of the Earth orbit and on how to manage it. The empirical economic literature on the orbit is still thin. Still, many authors point the need for more accurate data that is often lacking in this field. The following paper uses some of these data to produce an assessment of satellite collision losses.

Adilov et al. (2023) uses a computational model and data on satellites from the UCS

and the DISCOS databases.⁴⁵ The value of each satellite is estimated from its mass. The probability of collision between each satellite and a debris large enough to threaten it is obtained from the orbital environment model “MASTER”. The expected losses of an orbit are calculated by summing the expected losses for each satellite. The expected annual loss for all orbits was estimated \$86-103 million in 2020. Low Earth orbit represented roughly a fourth of the total value of satellites in orbit, but the expected loss in this region accounted for a major part of the aggregated orbit, totalling \$79-102 million annually. This region of Earth’s orbit is by far the most crowded with debris, but this expected loss amounts to only 0.16% of the total value of satellites in LEO. They also highlight the fact that commercial satellites represented only one-third of expected total losses.

A new treaty regulating (and thus limiting) the use of space is often regarded as unlikely. For the moment, a completely optimal set of regulations is even less likely. Comparing the outcome of several regulations with a cost low enough (e.g., a low tax rate) to be implemented in a not too long future may thus be of interest. The next paper considers such a situation and the expected effect on the space debris dynamics.

Adilov, Alexander and Cunningham (2020) aims to provide an evaluation of the effectiveness of several policy scenarios up to year 2100. Satellite launches are endogenous, and depend on the economic incentives their operator will be facing. The debris considered are only 10 cm and larger. They include several regulatory tools in their simulations: a 10 to 15% launch tax, an improved compliance rate to the end-of-life guidelines (i.e. a time limit for unproductive satellites to quit the protected orbital area), and a debris removal, starting from two pieces of debris in 2021 and then increasing at a rate of 9% per year. They show that neither such a weak launch tax nor a compliance rate improved to 95% would be enough by themselves to start to stop the rise in the number of debris in orbit. According to their results, only scenarios including debris removals would be able to decrease the number of threatening objects.

Discussions between the regulator and the industry are usually at the core of the creation and evolution of regulations. A private industry usually pushes back regulations that would decrease its expected revenue. The space debris pollution has an important specificity: its negative externality affects the assets of the satellite industry itself. This can be regarded as positive, as the industry could be convinced of its own interest to enforce a cleaner use of the orbit. The work discussed below provides data that could incentivise the industry to take this path.

Rao, Burgess and Kaffine (2020) use a coupled physical-economic model to simulate the orbital trajectories up to year 2040. Satellite launches are endogenous and depends on economic incentives. These incentives themselves depend on the endogenous risk of collision

⁴⁵DISCOS stands for “Database and Information System Characterising Objects in Space”.

because of the induced decreased of the expected operational lifetime. As the stock of debris grows, the value of the space industry decreases. An orbital-use fee that consists in a tax paid for satellites for each period spent in orbit is proposed. This fee is set to maximise the long-run value of the satellite fleet. The authors argue that economic incentives should target objects in orbit rather than launches. They support their declaration by the fact that objects in orbit are the one that increase the risk of collision. For this reason, an efficient instrument should disincentivise to increase their stock. They compare a business-as-usual scenario with a regulated one, where the orbital-use fee is implemented. They show that the fee should increase over the years, up to \$325,000 per satellite per year in 2040. Contrary to a technological solution to mitigate the issue that would cause a rebound effect, they find that this monetary incentive would increase the efficiency of orbit-use. According to their work, thanks to this regulation, the net value of the satellite industry could more than quadruple in year 2040, going from a \$600 billion to around \$3 trillion.

A satellite industry that would cooperate in a syndicate could welcome an optimal regulation of the orbit. However, an industry that does not cooperate would not lead to the desired result. Consider an industry split into several entities, whether companies or states. As some would be more incentivised to invest on cleaner technologies, or to clean the space (e.g., because their share of the economic activity is greater) their foes could adopt the behaviour of a free-rider. The cleaner behaviour of the said entities itself becomes a common good that is not paid by other firms that would take benefit of it. Such a market failure, applied to space debris removal, is explored in the following paper.

Klima et al. (2018) studies the cost of anarchy in situation where a space actors can clean the orbit. Satellite launches are exogenous. They belong to several operators that all possess a given share of the fleet. Players decide on the level of effort depending on past actions, the current state of the environment, and budget limitations. They act to minimise the sum of the cost of their lost assets and their cost of removal efforts. The joint removal effort consists in a joint threshold. Any debris that would create more debris that the threshold in case of collision will be removed. A centralised solution lead to the best outcome by definition. When there are two players, the more equally they are in size, the bigger the inefficiency will be. However, they confirm that equally sized players will also lean to a fairer behaviour.

To guide policymakers, a precise understanding of the environment and of the impact of regulations is needed. Integrated Environmental Assessment models are important tools to guide the management of common-pool resources. The next paper consists in the presentation of a first sketch of such an integrated model.

Rao and Letizia (2021) consider a model of orbit split into several altitudes' shells. Their work is based on three components. The first one is physical model, including debris creation and collisions. Then, there is an econometric model of operators' demand for orbits, that is split in two stages. The first stage is a model of the total number of satellites launched in

each sector the space economy (i.e. commercial, civil government, and defence). The second stage is a model of operators' choices to launch satellites to specific shells, depending on their physical state and on economic parameters such as access costs. They demonstrate the ability of this type of model to study the space industry behaviour in response to several type of changes (i.e., an unexpected fragmentation in a highly used orbital region, a decreasing costs scenario, and a time increasing compliance with 25-year Post Mission Disposal guidelines).

1.5 Summary of work

1.5.1 The questions of optimal satellite design and orbit depollution

This subsection focuses on the paper provided in Chapter 2, titled “Sustainable management of space activity in low Earth orbit”, coauthored with Sébastien Rouillon, and published the 12 July 2023 in the *Journal of Environmental Economics and Policy*. It will be referred to as Guyot and Rouillon (2023) afterwards.

This work extends the analysis of Rouillon (2020). As such, contrary to the rest of the economic literature that considers the orbital environment on a limited horizon, it focuses on the long-run state. This approach allows to highlight the specificities of a sustainable path, by contrast to the short- or medium-term dynamics of the satellite industry.

As in Rouillon (2020), the physical model proposed for modelling the orbit is described by three populations. Active (i.e. operational) satellites are distinguished from inactive satellites (i.e. large debris, either satellite remnants or upper stage rockets). An active satellite that suffers an electronic or mechanical failure becomes an inactive satellite at a given rate. Otherwise, it is instantly deorbited, accounting for the compliance with end-of-life good practices. Unlike other models where satellites are infinitely lived (e.g., Rao and Rondina (2022)), modelling an operational lifetime that does not uniquely depend on the orbital pollution more realistically represents the satellite operators incentives. Any long-term modelling of the orbit that would abstract from the natural failure of a satellite would highly overstate the difference between low-pollution orbital environment (where satellites could theoretically survive for a very long time before a collision occurs) and a medium or high-pollution environment. Likewise, it allows a more realistic approach of the physical pollution than models where inactive satellites are instantly disposed of (e.g., Adilov, Alexander and Cunningham, 2018). These two populations are at risk of collisions with smaller debris fragments. Collisions happen between debris fragments and both active and inactive satellites. On collision, a satellite breaks-up in a large number of debris fragments. Both debris fragment and inactive satellites decay by falling towards Earth. For inactive satellites, this natural decay can be coupled with active debris removals. In addition to putting satellites into orbit, launches generate some debris fragments and left upper stage rockets in orbit.

Satellite operators are private entities that maximise their own profits and disregard the external cost they impose on others. In the long run, the collision rate increases with the launch rate, on a magnitude that depends on the physical mechanisms discussed above. As the collision rate increases, the expected operational lifetime of a satellite decreases. This consequently decreases its expected value at launch. The launch rate is thus the first behaviour variable through which satellite operators will affect both the orbital environment and the economic outcome. The launch rate and the economic incentives to decrease it through a

launch tax to a socially optimal level have been a primary focus of the space debris literature (i.e., Adilov, Alexander and Cunningham, 2015, Adilov, Alexander and Cunningham, 2020, Béal, Deschamps and Moulin, 2020, Rouillon, 2020). However, the launch rate is not the only variable that will impact the orbital environment. This paper considers two other channels of externalities that could be controlled in order to increase the efficiency of the satellite industry.

The long-run size of the satellite fleet is an increasing and concave function of the launch rate. It depends on two parameters: the collision rate and the failure rate. The rate of technical failure defines the intrinsic lifetime of a satellite. By using better components and by improving its design, satellites can be designed to lead to a lower failure rate and vice versa. This is endogenously chosen by the satellite operator. This second variable will also influence the collision rate. As the operational lifetime of a satellite increases, so does the probability that a launch will generate a supplementary collision. On the one hand, because of the increased externality, this will reduce the incentive to launch a satellite, all other things being equal. On the other hand, a longer operational lifetime directly increases the incentive to launch a satellite thanks to its effect on the expected profit. The conception of higher quality satellites is costly. The cost of a satellite increases at an increasing rate with its intrinsic lifetime. Satellite design is thus the second channel through which the externality can be affected.

The third channel is the active debris removal. A cleaning industry that would remove a portion of inactive satellites each period can be financed by a regulator. The physical effect is identical to an increase of the speed of inactive satellites decay. By doing so, the regulator can reduce the expected long-run externality for a given launch rate.

The first channel of the externality, the launch rate, can be controlled by a launch tax, as previously discussed. A second economic instrument is proposed to incentive satellite operators to design their satellites optimally. As it is unrealistic to assume that the regulator can control the reliability of all satellites *ex ante*, it is proposed to use an *ad valorem* tax. This tax applies to the satellite revenue, i.e. a fee proportional to the satellite revenue is paid each year. As the total value paid varies with the operational lifetime of a satellite, this tax can incentivise to increase or decrease the satellite quality, in addition to incentivise to decrease the launch rate. This *ad valorem* tax is different from the orbital-use fee proposed by Rao, Burgess and Kaffine (2020). An orbital-use fee would also incentivise to decrease the time an end-of-life satellite would stay in orbit.

The third proposed economic instrument through which the externality can be affected is a market of depollution certifications. The debris removal activity cost depends on the increase of the natural decay. A market for removal effort certificates fund services for the removal of end-of-life satellites. Satellite operators have to buy a given number of them to launch a satellite. A labelling agency issues the certificates that can be traded on the

market. By setting the number of certificates required to launch a satellite, the regulator defines the level of debris removal effort. This effort increases the mean speed before an end-of-life satellite is removed. Contrary to Béal, Deschamps and Moulin (2020) and Bernhard, Deschamps and Zaccour (2023) where an optimal launch tax may not be enough to finance the debris removal activities, this market of certificates is by definition balanced.

The open access physico-economic equilibrium is compared to the optimal situation. An optimal value of the optimal economic instruments incentivise the satellite operators and the removal market to maximise the well-being derived from the orbit-use. Their formal expression is calculated. Finally, a set of simulations have been carried based on a realistic calibration. As debris removal technologies are still in development, a sensitivity analysis based on a varying unit cost of removal effort has been carried out.

An extension considering imperfect competition completes the analysis. The atomicity assumption is lifted, meaning that satellite operators might implement strategic behaviours. In this situation, the orbit users can have an incentive to limit the proliferation of debris in orbit. Their mitigation strategies are shown to be suboptimal, because they only receive a fraction of the external benefit they generate, confirming a result of the common good problem and the work of Klima et al. (2018). A second reason is that, as the externality affects the asset value of satellite operators in the long run, a debris mitigation measure increases the long-run size of the fleet, thus diminishing the price of the service. Finally, it is shown that the efficiency of the orbit-use decreases with the number of competitors.

1.5.2 The creation of a multi-layer model

This subsection focuses on the paper provided in Chapter 3, titled “A layered model of the long-run orbit use”, has been sent to the *Acta Astronautica* journal. It will be referred to as Guyot (2024) afterwards.

This model is a supplementary extension of Rouillon (2020). The focus is still on the long-run steady state. The physical model consists of the same three populations: active satellites, inactive satellites, and debris fragments. Low Earth orbit is layered into 18 shells of altitude going from 200 to 2000 km. Satellites launches generate both debris fragments and inactive satellites as a by-product. Debris fragments can collide with both active and inactive satellites. A collision breaks-up a satellite in a large number of debris fragments. The model is simpler than Guyot and Rouillon (2023) for the sake of analytical resolution. When a failure occurs, an active satellite always become an inactive satellite. Inactive satellites do not decay. For a collision rate high enough, this assumption is pretty realistic, as the probability for a satellite to survive long enough to fall back is not significant. The physics between the layers are modelled as follows. Rather than falling straight back to earth, debris fragments fall back into the layer below. Except for the highest one, each layer thus receives a constant and continuous flow debris in the long run.

With the exception of Rao and Letizia (2021) every economic model considers the orbit (or low Earth orbit) taken as a whole. Yet, as Bongers and Torres (2023) pointed out, the altitude of a satellite plays an important role. Indeed, a lower altitude increases the decay of debris fragments. Consequently, launching satellites at a lower altitude will result in a smaller negative externality, as the long-run steady stock of debris will be smaller. When the orbit is taken as a whole, the parameters for debris decay have to be estimated from the current debris decay rate. However, today's debris are at an altitude that depends on the satellites launch previously. If the altitude of newly sent satellites is different, the future rate of decay will differ.⁴⁶ For this reason, the altitude choice made by satellite operators is a significant variable to efficiently regulate the orbit.

The altitude choice materialises another market failure. As satellites operators disregard the externality of their satellites on others, too many satellites will be placed at a higher altitude. If they suffer a collision, the debris fragments created at a given altitude will first threaten satellites at this altitude and then fall back, thus threatening satellites at lower altitudes. By doing so, they may disincentivise the use of lower (and more efficient) altitude shells.

As in Rouillon (2020) and Guyot and Rouillon (2023), the long-run stock of debris depends on the launch rate, the intrinsic planned lifetime of a satellite, and the collision rate. The cost of launching a satellite is assumed to depend on two parts. First, the cost to design and manufacture a representative satellite. Then, a varying part, that depends on both the cost to launch a satellite (that increases with altitude) and the cost to make a satellite that can maintain itself at its assigned altitude (that decreases with altitude, because of a lowered atmospheric drag). The decrease from the decreasing cost to maintain a satellite in orbit is assumed to be bigger than the increase from the increasing cost of launch at first. Then, the situation reverses. As such, the cost function is first decreasing and then increasing with altitude.

The equilibrium resulting from the behaviours of satellite operators in open access is compared to the optimal allocation. The modelling of the exchanges of space debris between layers and the physical parameters varying with altitudes allows to give a new light to past results concerning the optimal management of the orbit. In the long run, it is shown that some layers that should be used in the optimal scenario might not be used within an open access management. The reason is that, if the orbit is left unregulated, satellite operators might overuse the highest layers of orbit because they disregard the external cost imposed on the lower layers and because it would minimise the external cost imposed on them by the others. This extreme case demonstrates the need for an economic incentive that corrects the market failure emerging from this dimension. The results show that an optimal launch tax

⁴⁶This is what is happening today, as both the two new largest constellations lower the average altitude of the satellite fleet in orbit.

should differ with the satellite operator’s altitude choice. A numerical illustration based on a realistic calibration showcases the analytical analysis. Because of the uncertainty of the evolution of both revenues and cost relating to orbit-use, a sensitivity analysis based on the satellite revenue is provided, illustrating a varying demand for satellite services.

1.5.3 The question of competition between the large constellations

This subsection focuses on the paper provided in Chapter 4, titled “Oligopoly competition between satellite constellations will reduce economic welfare from orbit-use”, and published the 16 October 2023 in the Proceedings of the National Academy of Sciences. It will be referred to as Guyot, Rao and Rouillon (2023) afterwards.

The rise of new large constellations has been changing the competition on some areas of low Earth orbit. From a situation where a number of satellite operators proposing distinct satellite services, the fleet in low Earth orbit is now largely dominated by two constellations. Most of the literature focused on a perfectly competitive market (Adilov, Alexander and Cunningham, 2018, Béal, Deschamps and Moulin, 2020, Bongers and Torres, 2023, Grzelka and Wagner, 2019, Macauley, 2015, Rao and Rondina, 2022, Rouillon, 2020). Klima et al. (2018) only models the strategic behaviours of orbital users toward debris removals, while the launch rate is exogenous. Bernhard, Deschamps and Zaccour (2023) studies the strategic interactions of two satellite mega constellations in a situation where they impose a congestion cost on each other’s. However, both constellations operate at the same altitude, and the quality of service they offer is not directly explored.

This oligopolistic evolution raises new questions about the congestion of the orbit. But much less attention has been devoted to the economic consequences for the consumers of a market concentrated in the hands of a few competitors. This work proposes to study a duopoly competition between two firms operating a large constellation each where both firms can differentiate their services. Both constellations provide telecommunications services. The economic model represents both the microeconomic behaviours of the operators and a heterogeneous demand.

Consumers are distributed according to their willingness to pay. Satellite operators compete for consumers and choose their price to maximise their benefit. Consumers maximise their utility by choosing the service (i.e. the constellation) that will provide them with the most satisfaction given service characteristics (i.e. quality of service) and prices. The quality of service provided by a constellation depends on three dimensions. First, its availability, that refers to the fraction of time a service is available. It depends on its coverage area (that vary with the constellation altitude and sizes) and on collision avoidance manoeuvres. Second, its latency, that refers to the mean time for the signal to travel from the consumer to the nearest satellite of the constellation. It depends on both the size and the altitude of the constellation. Third, its bandwidth that refers to the data transmission rate. It varies

with the ratio of satellites to consumers.

The orbit is layered in several shells of altitude. Firms choose the altitude and size of their fleet, affecting the quality of service they offer. If the two constellations are placed too close to each other, the satellites of both constellations will have to manoeuvre to avoid collision. These manoeuvres can also happen for satellites in the same constellation. Larger constellations mean more manoeuvres, during which the satellites are not able to provide its service, thus decreasing the service availability. Constellations are built considering a trade-off between the components of the quality of service. For example, a satellite at an higher altitude might provide a better coverage thus increasing the quality of service, but a constellation at a higher altitude also increases the latency, decreasing the quality of service.

The cost to deploy and maintain a constellation also takes part in the trade-off faced by both firms. On the one hand, the atmospheric drag decreases with altitude, thus making it cheaper to maintain a satellite at its operating altitude during its lifetime. On the other hand, the cost to deploy a satellite increases with the chosen altitude. The interaction between the two makes the cost of a satellite first decreasing and then increasing with altitude.

Firms compete in two stages: first in a sequential-move location-and-size-choice game and second in a simultaneous-move price-setting game. A firm is the leader (the first one to deploy its constellation) that anticipates the follower's entry and chooses the location and size of its constellation first to maximise its profit. The follower does so by adapting to the leader choice. Firms are forward-looking and anticipate the outcomes of the pricing subgame when making their choices.

Three scenarios are considered: the duopoly equilibrium resulting from the competition of both firms, a unique public utility constellation, and a public utility composed of two constellations. A public utility is defined as a constellation system that aims to maximises public welfare. A two constellations public utility is necessary to account for the potential gains from regulation while providing differentiated service. Numerical simulations are carried using realistic calibration. A sensitivity analysis considering the environmental damage costs⁴⁷ of satellites is also provided.⁴⁸

At the duopoly equilibrium, the leader firm is able to claim the best altitude shell. The leader firm fleet size is much larger than the follower's one. A large distance separates the altitudes of the two constellations — much more than needed in order to avoid collision avoidance between the two fleets. This illustrates the logic of competition in vertically-differentiated markets, where increasing the differentiation between the service offerings increases both

⁴⁷These damage costs encapsulate the annualized value of various environmental externalities other than orbital congestion, such as rocket emissions, orbital debris, ozone layer degradation, and re-entry impacts on people and property.

⁴⁸Compared to the open access, an imperfect competition might improve the environmental problem of space debris, but still less than with a centralised solution.

firms' profits, as it decreases the "toughness" of competition between the two for indifferent consumers.

In the two-constellation public utility system, both firms place their constellations near the altitude where the cost of launching and operating a satellite is the smallest. There are just distant enough to avoid between-constellation congestion. The size differentiation between both fleets is also smaller. The number of satellites in orbit is almost the same with the two-constellation public utility system than with the one-constellation public utility system. However, a two-constellation public utility offers the possibility of providing a differentiated service by taking into account the heterogeneity of the consumers. It also allows to decrease the space congestion, by splitting the fleet into two locations. Both public utility systems consist in a larger number of satellites in orbit than in the duopoly case.

As the environmental damages increase, the public utilities progressively decrease their constellation sizes. Beyond a critical point, the two-constellation public utility then transitions to a single constellation. The total number of satellites in the public utility systems become smaller than in the duopoly case at approximately \$150,000 of environmental damage cost per satellite per year.

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Chapter 2

Sustainable management of space activity in low Earth orbit

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Abstract

This paper extends the analysis initiated by Rouillon (2020) of the externality caused by space debris. Satellite operators make choices about the design and launch of satellites, while in-orbit servicing firms supply efforts to remove space debris. Focusing on the long-term orbital state, we compare two management regimes. The open access equilibrium occurs when the orbit is a common resource. The optimal policy maximizes the net present value generated periodically by the space industry. We investigate economic instruments capable of effectively regulating space activity. We show that the combination of an ad valorem tax, a launch tax, and a market for removal effort certificates can provide the right incentives. A numerical application using a realistic calibration illustrates our results.

Keywords: Space economics, orbital debris, sustainability.

2.1 Introduction

Although already crowded, several large constellation projects are currently targeting low Earth orbits. This accumulation of artificial satellites and debris may eventually penalize future space missions. Adilov, Alexander and Cunningham (2020) identifies the foreseeable costs of such pollution, whether direct (i.e., reduction of the life span of satellites), financial (i.e., insurance premiums) or adaptation (i.e., shielding, surveillance systems, avoidance manoeuvres, removal of objects). Without an appropriate regulation, the well-known tragedy of the commons scenario, described by Hardin (1968), risks repeating itself. The scientific literature predicts the evolution of the state of the Earth’s orbit in the short and medium term (Cordelli et al., 1993, Dolado-Perez, Pardini and Anselmo, 2015). In a catastrophic scenario, known as the Kessler syndrom (Kessler and Cour-Palais, 1978), the orbit could even become unusable. These alarms have prompted the United Nations (2010) to call for the sustainable exploitation of Earth orbits. The economic literature has recently taken up these issues, to which this article intends to contribute.

This paper extends Rouillon (2020), which focused on launch rates and treated debris removal exogenously. Here, we additionally include design choices and removal services as endogenous variables.¹ Manufacturers adjust the risk of failure by selecting the quality of their satellite components. A more reliable satellite costs more but will generate more revenue over its longer operational life. Unfortunately, this also fosters an increased risk of collision. This article also considers end-of-life satellite removal efforts performed by in-orbit service companies.

Methodologically, the approach is identical to that of Rouillon (2020). We analyze the long-term equilibrium of the orbit, assuming constant launch rate, design choice and removal rate over time. We then compare two orbit management regimes. The open access equilibrium reflects the choices of the space sector in the absence of regulation. The optimal policy describes choices that maximize the value produced periodically by space activity. Under open access, the space sector makes suboptimal choices, by neglecting their effects on collision risks. As a result, operators launch too many satellites with too short a lifetime, and no removal effort is made. To correct these externalities, we show that three incentive instruments must be associated. An ad valorem tax guides the design choices. A launch tax is used to slow down the rate of satellite launches. A market for removal effort certificates fund services for the removal of end-of-life satellites.

Since the pioneering paper by Kessler and Cour-Palais (1978), several physical models have been developed to simulate the short- and medium-term evolution of orbital pollution (e.g., Drmola and Hubik, 2018, Le May et al., 2018, Lucken and Giolito, 2019, Somma, Lewis and Colombo, 2019). In parallel, simplified models have been developed to qualitatively

¹Mark and Kamath (2019) produced a review of space object removal methods.

analyze the underlying dynamical properties (Farinella and Cordelli, 1991, Lafleur, 2011, Percy, 2015, and Rouillon, 2020). Overall, these tools teach us that the current trends are unsustainable, calling for additional regulation. For example, Virgili et al. (2016) shows that the current voluntary space debris mitigation guidelines will not prevent the proliferation of debris. Adilov, Alexander and Cunningham (2020) add that sustainable orbit management by the end of the century require complementary measures, such as tax incentives and an effort to remove inactive objects.

The economic literature is recent but rapidly developing. Adilov, Alexander and Cunningham (2018) shows that orbital activity will cease to be profitable before the Kessler syndrome. Bongers and Torres (2023) provide an estimate of the maximum number of satellites triggering a Kessler syndrome. The design of a regulatory framework to mitigate of orbital pollution is a central issue in the economic literature (Adilov, Alexander and Cunningham, 2015 and 2020, Béal, Deschamps and Moulin, 2020, Bernhard, Deschamps and Zaccour, 2023, Grzelka and Wagner, 2019, Macauley, 2015, Rao, Burgess and Kaffine, 2020, Rouillon, 2020). Most contributions recommend implementing a launch tax (Adilov, Alexander and Cunningham, 2015, Béal, Deschamps and Moulin, 2020, Rouillon, 2020) or an orbit-use tax (Rao, Burgess and Kaffine, 2020). The main justification is to force the space sector to internalize external costs. Other benefits are also explored. Macauley (2015) argues that a tax levied at launch and then rebated contingent on some mitigation actions (e.g., collision-proof satellite design, end-of-life de-orbit) can be more effective. Béal, Deschamps and Moulin (2020) and Bernhard, Deschamps and Zaccour (2023) suggest allocating the taxes collected to finance the removal of debris. Command-and-control measures are also discussed, with the usual caveats (Adilov, Alexander and Cunningham, 2015, Rao, Burgess and Kaffine, 2020, Rouillon, 2020). Such solutions taken alone may trigger a rebound effect, with the restoration of the profitability pushing operators to make detrimental choices. Finally, Grzelka and Wagner (2019) highlight how intellectual property rights can support innovations in cleaner satellite design.

This paper offers new perspectives on the regulation of space activity. First, it focuses on the long-term orbital state to address the issue of sustainability. Most of the literature either considers a limited horizon (Adilov, Alexander and Cunningham, 2015, Grzelka and Wagner, 2019, Macauley, 2015) or deals with orbital pollution in the short and medium term (Adilov, Alexander and Cunningham, 2018 and 2020, Béal, Deschamps and Moulin, 2020, Muller, Rozanova and Urdanoz, 2017, Rao, Burgess and Kaffine, 2020). Second, we endogenize three behavioural variables influencing debris accumulation (i.e., design and launch of operational satellites and removal of end-of-life satellites). In the literature, design choices (Grzelka and Wagner, 2019, Macauley, 2015, Rouillon, 2020) and removal activities (Adilov, Alexander and Cunningham, 2020, Béal, Deschamps and Moulin, 2020, Bernhard, Deschamps and Zaccour, 2023, Muller, Rozanova and Urdanoz, 2017, Rao, Burgess and Kaffine, 2020, Rouillon, 2020)

are never considered together and most often treated as exogenous. Third, and consequently, we identify three vectors of externalities, each requiring a dedicated incentive instrument. We propose and compute such a set of instruments (i.e., ad valorem and launch taxes and a market for removal certificates). In contrast, Rouillon (2020) compared alternative instruments (i.e., a global launch quota, a launch tax, and a market of individual transferable launch quotas) to regulate the launch rate as the only vector of externality. The current work therefore expands the range of tools available to regulate orbital pollution. Finally, although on a purely technical level, our physical model is the only one to explicitly separate operational and end-of-life orbiting satellites, allowing to distinguish operational and orbital lifetimes.

This paper is organized as follows. Section 2 describes our model. Section 3 presents several physical indicators. Section 4 characterizes the open access physico-economic equilibrium. Section 5 derives the optimal policy. Section 6 proposes economic instruments to regulate space activity. In Section 7, we give a numerical application. In Section 8 extends the numerical application by considering that satellite operators act strategically. Section 9 concludes. Supplementary materials and proofs are supplied in an appendix.

2.2 The model

Consider the space activity in low Earth orbit.² Assume that the space sector continuously launches q satellites per period.³ The operational lifetime of a satellite orbiting the Earth depends on technical (i.e., components failure) and environmental (i.e., collisions) events. Below, it is formalized as the minimum of two independent random variables T_λ and T_μ , respectively giving the durations before a failure and a collision, with exponential probability distribution functions $1 - e^{-\lambda t}$ and $1 - e^{-\mu t}$.⁴ The rate of technical failure λ is endogenously chosen by the satellite designer.⁵ At the end of their mission, defect satellites remaining in orbit fall back to Earth naturally, unless they are actively removed before that.⁶ We denote by r the removal effort made periodically by the space sector.⁷ The rate of collision μ depends

²Low Earth orbit is at altitudes between 200 and 2,000 km. The reason we focus on this region is that it is already very crowded with debris and highly coveted by the space industry. We also ignored medium and geostationary orbits because the physical and economic heterogeneity between orbital regions (i.e., decay rate, launch cost, satellite design) would affect the quality of our results.

³Satellites differ in many respects (mass, surface, power, etc.). To account for this diversity, we assume that satellites can be produced at different scales (from large to nano satellites), making the launch rate a continuous variable.

⁴The operational lifetime $\min\{T_\lambda, T_\mu\}$ is distributed according to $1 - e^{-(\lambda+\mu)t}$.

⁵Equivalently, the operator chooses the intrinsic lifetime, equal to $1/\lambda$.

⁶The duration of the natural fallout of a satellite varies from decades to centuries depending on the altitude.

⁷In our physical model (see appendix A1), the removal activity causes inactive objects to decay at rate r . Thus, a cleaning effort r is equivalent to removing a fraction $1 - e^{-r}$ of inactive objects currently in orbit in one year. Alternatively, this is equivalent to removing inactive objects in an average of $1/r$ years after their mission ends.

on the state of the orbit, as explained below. In case of collision, satellites disintegrate, releasing η fragments in the orbital shell, an exogenous parameter.

Following Rouillon (2020), we focus on the equilibrium of the orbital environment, resulting in the long run from an assumed constant launch and removal rate q and r , each satellite having a failure rate λ . In this way, suppose that there exists a relationship $x = \phi(\lambda, q, r)$, giving the long-term stock of debris fragments, once the orbit has reached its steady state. Assume further that there exists a relationship $\mu = \varphi(x)$, giving the instantaneous risk of collision as a function of the latter population. Overall, this formalization drives us to conclude that the long-run risk of collision, can be written as $\mu = \mu(\lambda, q, r)$, where we let $\mu(\lambda, q, r) \equiv \varphi(\phi(\lambda, q, r))$ for notational convenience.

Many factors are likely to determine this relationship. Some are under the control of the satellite operators (e.g., altitudes, innovations, mitigation and remediation measures), while others are not (e.g., atmospheric density, solar activity). Most are left implicit here, in order to focus on the economic intuitions. Still, we describe in the appendix a simplified physical model rationalizing our approach.

Thereafter, we will simply postulate the following:⁸

Assumption 1. The risk of collision $\mu(\lambda, q, r)$ is decreasing in λ and r , and increasing in q . Formally, $\mu_\lambda(\lambda, q, r) < 0$, $\mu_q(\lambda, q, r) > 0$ and $\mu_r(\lambda, q, r) < 0$, for all λ , q and r .

The intuitions supporting it are the following. The risk of a satellite being destroyed increases with the time spent in orbit and the density of debris fragments. Since an increased failure rate or a quicker removal leads to a smaller orbital lifetime, it is understandable that μ decreases with λ and r . On the other hand, as debris fragments ultimately come from destroyed rocket bodies and satellites, it is understandable that μ increases with q .

The basic players in our economic model are satellite operators and in-orbit servicing companies. The former order satellites from manufacturers and request launchers to place them in orbit. They then lease the services produced by their fleet to consumers. The latter use spacecrafts that travel through low Earth orbit to remove inactive objects. Until Section 2.8, it is assumed that the entry and exit into and out of both markets are free and without cost. The maximum number of potential firms is assumed to be sufficiently large.⁹

Below, the economic parameters at stake are the following. The unit cost of a satellite with a failure rate λ is given by $c(\lambda)$.¹⁰ The cost of removal per unit of effort is d .¹¹ The

⁸This assumption is justified in appendix A1.

⁹Rouillon (2020) found 67 operators owning the 589 commercial satellites in low Earth orbit in 2018. Updated today (UCS, 2022), we count 162 operators and 3797 commercial satellites. Additional data describing recent developments in the satellite services market are available in a supplementary material in an appendix.

¹⁰Cost $c(\lambda)$ is the counterpart of the remuneration of subcontractors for the manufacture and placing in orbit of the satellite. It therefore includes the cost of design, construction, testing, launch and insurance.

¹¹From footnote 7, a cleaning effort $r = 1$ means removing $1 - 1/e \simeq 63$ % of currently end-of-life objects

rent paid per unit of time by consumers for satellite services, less operating costs, is equal to p .¹² The economic agents are assumed to discount time at the rate of time preference δ .

Thereafter, we will use the following:

Assumption 2. Let $\underline{\lambda}$ and $\bar{\lambda}$ be such that $0 \leq \underline{\lambda} < \bar{\lambda}$. (i) The unit cost $c(\lambda)$ is strictly decreasing and convex for all $\lambda \in [\underline{\lambda}, \bar{\lambda}]$; (ii) $\lim_{\lambda \rightarrow \underline{\lambda}} c'(\lambda) = -\infty$ and $\lim_{\lambda \rightarrow \bar{\lambda}} c'(\lambda) = 0$.

Accordingly, the satellite operators can design satellites with parameters λ between $\underline{\lambda}$ and $\bar{\lambda}$.¹³ Part (i) means that improving their reliability is costly, at an increasing rate. The least expensive satellite has a lifetime equal to $1/\bar{\lambda}$ and that the longest (technically and/or economically) possible lifetime is equal to $1/\underline{\lambda}$. Part (ii) simplifies the analysis by guaranteeing an interior solution.

2.3 Physical indicators

This section proposes several indicators to characterize the situation of the space activity, both at the satellite and orbital levels.

Consider a marginal satellite launched at any time t_0 .

In our analytical framework, the operational lifetime is the shortest time before the satellite fails or suffers a collision (i.e., $\min\{T_\lambda, T_\mu\}$). The latter being independent exponentially distributed random variables with rate parameters λ and μ , the expected operational lifetime of a satellite launched at any time t_0 is given by:

$$\int_{t_0}^{\infty} (\lambda + \mu) e^{-(\lambda + \mu)(t - t_0)} (t - t_0) dt.$$

Indeed, the satellite stops working when it fails or is destroyed by collision, which occurs at time $t > t_0$ with probability $(\lambda + \mu) e^{-(\lambda + \mu)(t - t_0)}$. Integrating this expression, we obtain:

$$D \equiv \frac{1}{\lambda + \mu}. \quad (2.1)$$

As $D = 1/\lambda$ when $\mu = 0$, the inverse of the failure rate can be interpreted as the satellite planned lifetime.

The probability of a satellite undergoing a collision before it fails is equal to:

in one year. By definition, parameter d gives the annual cost of the inputs required to achieve this. See Mark and Kamath (2019) for a survey of methods currently in development.

¹²Up to section 2.8, the market for satellite services is assumed perfectly competitive. Several arguments can justify this, at least as an approximation. First, competition in this market goes beyond the space sector, as most of these are also available by terrestrial means. Second, since the lifetime of a satellite ranges from 1 to 25 years (UCS, 2021), the addition or removal of satellites in a given year has a negligible effect compared to the size of the satellite fleet.

¹³This includes cases where $\underline{\lambda} = 0$ and/or $\bar{\lambda} = \infty$.

$$\int_{t_0}^{\infty} \left(\int_{t_0}^t \mu e^{-\mu(\tau-t_0)} d\tau \right) \lambda e^{-\lambda(t-t_0)} dt.$$

Indeed, the satellite fails at time $t > t_0$ with probability $\lambda e^{-\lambda(t-t_0)}$. In the meantime, it incurs a collision risk, at each instant τ , with probability $\mu e^{-\mu(\tau-t_0)}$. By integrating this expression, we get after simplification:

$$P \equiv \frac{\mu}{\lambda + \mu}. \quad (2.2)$$

Note that this can be seen as the product of the rate of collision, μ , times the expected operational lifetime of a satellite, D .

The *expected* population of operational satellites converges in the long run to:

$$\int_{-\infty}^{t_0} q e^{-(\lambda+\mu)(t_0-t)} dt.$$

Indeed, by assumption, the launch rate is equal to q forever. A satellite launched at time $t < t_0$ remains operational till t_0 with probability $e^{-(\lambda+\mu)(t_0-t)}$. The *expected* fleet of satellites at time t_0 is the sum of all generations t of satellites launched previously (i.e., q per period) weighted by their probability of being operational at time t_0 (i.e., $e^{-(\lambda+\mu)(t_0-t)}$). Integrating the above expression, we obtain that:

$$S \equiv \frac{q}{\lambda + \mu}. \quad (2.3)$$

Note that this can be written as the product of the rate of satellite launches, q , times the expected operational lifetime of a satellite, D .

2.4 Open access equilibrium

In this section, we investigate the private incentives of the space sector under open access. The satellite operators are free to design and launch as many satellites as they wish. Presumably, they will do so as long as they can expect a positive net present value per satellite. In addition, they are not responsible for the objects they leave in orbit and therefore have no obligation to remove them at the end of their mission.

Let us isolate a firm designing a marginal satellite with a failure rate λ and launching it at any time t_0 . Assume that the orbital environment is in its long run stationary state, resulting from the other firms' behavior. Thus, the risk of collision is $\mu^* = \mu(\lambda^*, q^*, r^*)$, where λ^* , q^* and r^* stand for their design, launch and cleaning decisions.¹⁴

The considered satellite operator bears an immediate cost $c(\lambda)$ at time t_0 and anticipates to receive a cash-flow p during the satellite operational lifetime. Given that it discounts time

¹⁴This assumption will be abandoned in Section 2.8.

at the rate δ , the *expected* present value of its satellite is equal to:

$$\int_{t_0}^{\infty} \left(\int_{t_0}^t p e^{-\delta(\tau-t_0)} d\tau \right) (\lambda + \mu^*) e^{-(\lambda+\mu^*)(t-t_0)} dt.$$

Indeed, if it remains operational until time $t > t_0$, it generates a cash-flow equivalent to $\int_{t_0}^t p e^{-\delta(\tau-t_0)} d\tau$ in present value. It fails at time t with probability $(\lambda + \mu^*) e^{-(\lambda+\mu^*)(t-t_0)}$. By definition, the satellite *expected* present value is the sum of the product of these two terms over all possible failure times $t > t_0$. The above expression can be integrated, leaving:

$$\frac{p}{\delta + \lambda + \mu^*}. \quad (2.4)$$

In open access, our assumption is that operators will design their satellites to maximize their net present value and will launch more as long as the latter remains positive.¹⁵

On the one hand, each satellite operator will choose λ to maximize the *expected* net present value of their satellites:

$$\frac{p}{\delta + \lambda + \mu^*} - c(\lambda). \quad (2.5)$$

Focusing on a symmetric solution (i.e., $\lambda = \lambda^*$), the equilibrium choice satisfies:¹⁶

$$-\frac{p}{(\delta + \lambda^* + \mu^*)^2} - c'(\lambda^*) = 0. \quad (2.6)$$

Accordingly, the operators reduce the rate of failure up to the point where the associated private marginal cost (i.e., $-c'(\lambda^*)$) equals the marginal benefit from a longer operational life (i.e., $p/(\delta + \lambda^* + \mu^*)^2$).

On the other hand, satellite operators wish to launch more satellites as long as they earn a positive net present value per unit. Therefore, they will be satisfied with their plan when the launch rate q^* satisfies:

$$\frac{p}{\delta + \lambda^* + \mu^*} - c(\lambda^*) = 0. \quad (2.7)$$

In other words, satellite operators launch satellites until the present value of a satellite (i.e., $p/(\delta + \lambda^* + \mu^*)$) equals its unit cost (i.e., $c(\lambda^*)$).

Finally, the removal sector has no incentive to clean up the orbit. Indeed, the cost of a marginal effort is d . However, no demand will emerge for this service because the associated benefit is negligible at the scale of individual satellite operators. Therefore, the space sector will implement a removal effort r^* satisfying:

¹⁵Either incumbent operators will expand their fleet or entrants will build up their own fleet.

¹⁶The second-order condition $2p/(\delta + \lambda^* + \mu^*)^3 - c''(\lambda^*) < 0$ is sufficient for design choice $\lambda = \lambda^*$ to be a local maximum.

$$r^* = 0. \quad (2.8)$$

We summarize our ideas in the following:

Definition 1. A physico-economic equilibrium refers to decisions λ^* , q^* and r^* that satellite operators and removal companies would implement in their own interest.

Proposition 1. Under open access, a physico-economic equilibrium must satisfy conditions (2.6) to (2.8).

A clarification of (2.7) may be useful to avoid misinterpretation. At a physico-economic equilibrium, the satellite fleet remains constant at level $S^* = q^*/(\lambda^* + \mu^*)$ (by equation (2.3)). This results in the satellite operators spending $c(\lambda^*)q^*$ and collecting revenues equal to pS^* per period. Now, using condition (2.7), we show that:

$$pS^* - c(\lambda^*)q^* = \delta \frac{pS^*}{\delta + \lambda^* + \mu^*} > 0. \quad (2.9)$$

A first lesson is that the satellite operators generate a strictly positive operating surplus. Now, recall that the current satellite fleet of any generation t_0 declines in time, at a rate $\lambda^* + \mu^*$. On the financial market, its capitalization reflects the present value of the flow of revenue $pS^*e^{-(\lambda^*+\mu^*)(t-t_0)}$ that it will generate in the future:

$$\int_{t_0}^{\infty} (pS^*e^{-(\lambda^*+\mu^*)(t-t_0)}) e^{-\delta(t-t_0)} dt = \frac{pS^*}{\delta + \lambda^* + \mu^*}.$$

Linking the two results, another lesson is that the annual operating surplus (2.9) compensates the forgone interests on the financial market, so that the satellite fleet is as interesting as any other financial asset.

We calculate in appendix A2 the comparative statics of the open access equilibrium. Our results are stated in the following property:

Proposition 2. An open access equilibrium λ^* , q^* and r^* satisfies:

- (i) The planned lifetime $1/\lambda^*$ does not depend on d or δ , and is decreasing in p ;
- (ii) The launch rate q^* does not depend on d , is decreasing in δ and increasing in p ;
- (iii) The removal effort r^* is always zero.

We comment this by isolating the effects of each parameter one after the other. Varying the cost d of removal effort has no effect, simply because r^* is always zero in an open access equilibrium. A larger discount rate δ has no effect on the planned lifetime $1/\lambda^*$, but induces a slowdown in the launch rate q^* . Intuitively, less patient operators assign less value to

satellites. In the short term (i.e., for μ^* unchanged), this justifies launching fewer satellites with shorter lifetimes. However, in the long term, both adjustments decrease the risk of collision μ^* . The reason why $1/\lambda^*$ is ultimately unaffected is because the decrease of μ^* exactly offsets the variation of δ .

An increase in the rental price p induces the operators to design less durable satellites and to launch more of them. The first effect may seem counterintuitive, but can be understood if the second one is large enough. In the short term (i.e., for μ^* unchanged), a higher price encourages to launch more satellites with a longer lifetime. However, in the long term, the collision rate μ^* increases both because longer-lived satellites undergo more collisions and more satellites are put into orbit. As a larger risk of collision favors the design of less durable satellites, our result shows that the long-term effect outweighs the short-term effect.

Figure 2.1, plotting the terms $p/(\delta + \lambda + \mu)^2$ and $-c'(\lambda)$ in equation (2.6), further illustrates the optimal design choice. At initial price p , it is given by λ^* , at the intersection between the two curves. An exogenous increase of the price towards p' translates the first curve upwards. The intersection thus moves to the left, determining λ' . Thus, a larger price makes it profitable to design satellites with a longer planned lifetime. However, in the long term, the risk of collision will increase, for example toward μ' . The first curve undergoes a new translation, this time downwards. The intersection moves to the right, determining λ'' . Property 1 proves that the long term effect dominates, so that in the end $\lambda'' > \lambda^*$.

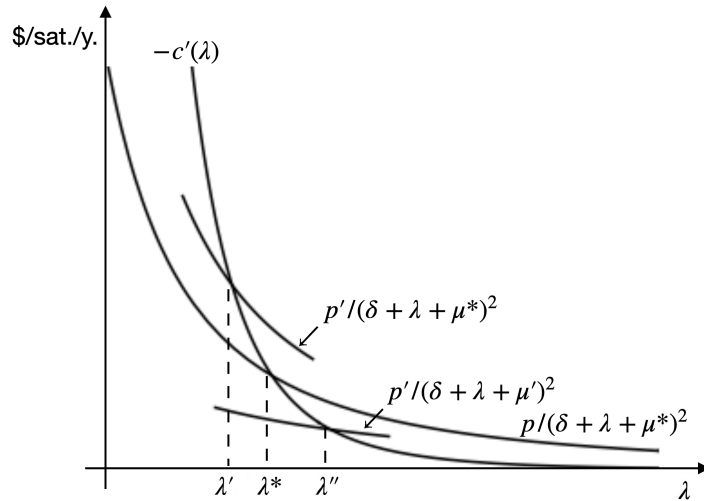


Figure 2.1: Optimal design

2.5 Optimal policy

In this section, we propose a normative criterion defining a socially optimal allocation and derive conditions characterizing it.

At any time, by assumption, the space sector launches q satellites with failure rate λ , and exerts removal effort r . Each satellite costs $c(\lambda)$ and is worth $p/(\delta + \lambda + \mu)$. Therefore, each generation of satellites generates a net present value equal to $(p/(\delta + \lambda + \mu) - c(\lambda))q$. On another hand, the removal efforts cost dr . In the end, the space sector periodically generates an aggregate net present value:

$$\left(\frac{p}{\delta + \lambda + \mu} - c(\lambda) \right) q - dr, \quad (2.10)$$

where the risk of collision $\mu = \mu(\lambda, q, r)$ is seen as endogenous here.

Below, our postulate will be that the social objective should be to maximize (2.10).¹⁷ We will refer to the following:

Definition 2. An optimal policy refers to allocations λ^o , q^o and r^o that maximize the yearly net present value of space activity (2.10) subject to the constraints $\underline{\lambda} \leq \lambda \leq \bar{\lambda}$, $q \geq 0$ and $r \geq 0$.

Consider first the case where no removal activity is socially profitable (i.e., $r^o = 0$). Assuming an interior solution for the other variables (i.e., $\underline{\lambda} < \lambda^o < \bar{\lambda}$ and $q^o > 0$), an optimal policy must satisfy the first-order conditions:¹⁸

$$-\frac{p}{(\delta + \lambda^o + \mu^o)^2} - c'(\lambda^o) = \frac{\mu_\lambda^o p}{(\delta + \lambda^o + \mu^o)^2}, \quad (2.11)$$

$$\frac{p}{\delta + \lambda^o + \mu^o} - c(\lambda^o) = \frac{\mu_q^o p q^o}{(\delta + \lambda^o + \mu^o)^2}, \quad (2.12)$$

$$d \geq -\frac{\mu_r^o p q^o}{(\delta + \lambda^o + \mu^o)^2}. \quad (2.13)$$

The first equation means that the planned lifetime must be set to equalize the private marginal benefit of a longer operational life (i.e., $p/(\delta + \lambda^o + \mu^o)^2 + c'(\lambda^o)$) with its external marginal cost (i.e., $-\mu_\lambda^o p/(\delta + \lambda^o + \mu^o)^2$). The second condition means launching satellites until the net present value of a marginal satellite (i.e., $p/(\delta + \lambda^o + \mu^o) - c(\lambda^o)$) equals its external cost (i.e., $\mu_q^o p q^o/(\delta + \lambda^o + \mu^o)^2$). The last equation means that the cost of a marginal removal effort (i.e., d) is larger than its external benefit (i.e., $-\mu_r^o p q^o/(\delta + \lambda^o + \mu^o)^2$).

In the case where removal activity is socially profitable (i.e., $r^o > 0$), the same conditions apply, except that (2.13) must hold as an equality. Then, the private cost of a marginal removal effort (i.e., d) must be equal to its external benefit (i.e., $-\mu_r^o p q^o/(\delta + \lambda^o + \mu^o)^2$).

We summarize our results in the following proposition:¹⁹

¹⁷Alternatively, one may propose to maximize the yearly net revenue $(p/(\lambda + \mu) - c(\lambda))q - dr$. Our approach embeds it as a special case, for the two objectives coincide when $\delta = 0$.

¹⁸Below, notations μ^o , μ_λ^o , μ_q^o and μ_r^o should be read as $\mu(\lambda^o, q^o, r^o)$, $\mu_\lambda(\lambda^o, q^o, r^o)$, $\mu_q(\lambda^o, q^o, r^o)$ and $\mu_r(\lambda^o, q^o, r^o)$ respectively.

¹⁹A proof is given in appendix A3.

Proposition 3. Assume that: (i) $\mu(\lambda, q, r)$ is negligible for small enough q and (ii) $D = 1/(\lambda + \mu(\lambda, q, r))$ is decreasing in λ . If there exists λ such that $p/(\delta + \lambda) - c(\lambda) > 0$, the optimal policy is such that $\underline{\lambda} < \lambda^o < \bar{\lambda}$ and $q^o > 0$. It satisfies conditions (2.11) to (2.13), with the last condition verified as an equality whenever $r^o > 0$.

Assumptions (i) and (ii) are verified by our physical model in appendix. The former means that the risk of collision disappears in the long term for low enough launch rates. The latter means that less reliable satellites always have a shorter operational life in the long run. This is true even taking into account that satellites with shorter lifetimes are less likely to generate debris (i.e., $\mu_\lambda(\lambda, q, r) < 0$). Proposition 3 ensures that we will have an internal solution for λ^o and q^o (i.e., $\underline{\lambda} < \lambda^o < \bar{\lambda}$ and $q^o > 0$) if satellites can be launched at a profit in a risk-free environment. This is a natural assumption since, otherwise, the satellite industry would never be profitable.

2.6 Regulated equilibrium

In this section, we identify, describe and compute a set of economic instruments capable of aligning the private interests of the space industry with the social preference.²⁰²¹

In our model, the discrepancy between the open-access equilibrium and the optimal policy arises from the external effects of space sector choices on the collision risk. There are three channels of externalities, associated with λ , q and r , which will require as many incentive instruments. In practice, their regulation may be complicated by the fact that they may not be readily observable by the regulator.

Consider first the choice of the satellites' reliability λ . The operators' motivation is to determine their planned lifetime $1/\lambda$. This matters from the social point of view, because the risk of a satellite being destroyed by collision increases with its time in orbit. From equation (2.11), the operators should be charged $-\mu_\lambda^o p/(\delta + \lambda^o + \mu)^2$ per unit of failure rate to internalize this externality. However, it is unrealistic to assume that the regulator can control the reliability of all satellites ex ante. In practice, only their actual period of operation will be observable ex post and can therefore serve as a support for an incentive instrument. Below, this externality will be corrected by levying an ad valorem tax τ throughout the period of operation of the satellites.

²⁰We are aware that implementing an optimal regulation would require an international treaty, which is out of reach in the short term. Yet, we believe that its description remains helpful to guide the debate. Besides, to supplement it, we simulate alternative policies in Section 2.7. We thank two anonymous referees for suggesting this extension.

²¹As debris is the elementary vector of the externality, one might be tempted to regulate the space sector using a Pigouvian tax, levied on each marginal debris emitted, reflecting the associated intertemporal damage. In practice, such a system is not realistic, because the fragments generated by a satellite destruction are not detectable by radar below a size of 10 cm and can potentially cause cascading collisions.

Consider now the launch rate q . The operators gain by launching more as long as the net present value of a marginal satellite is positive. The social cost comes from the fact that each satellite is a potential reservoir of future debris. From equation (2.12), the satellite operators should be charged $\mu_q^o p q^o / (\delta + \lambda^o + \mu)^2$ per satellite to internalize it. Below, this externality will be addressed by a launch tax l paid at the time of launch.

Finally consider the removal effort r . A unit effort to clean the orbit costs d , whereas the benefit is essentially external. Equation (2.13) reveals that the removal sector should be paid $-\mu_r^o p q^o / (\delta + \lambda^o + \mu)^2$ per unit of effort. Below, this externality will be corrected as follows. In-orbit servicing companies first choose their removal effort. In return, a labelling agency issues them removal effort certificates. These can be traded on a market at price s . Finally, satellite operators are required to obtain ε certificates per satellite to comply with the regulation.

We analyze below the behavior of the space sector subject to this regulatory framework. We first characterize the choices of satellite operators. We then derive the equilibrium of the market for removal effort certificates.

Let us first proceed to update the calculus of the *expected* net present value of a marginal satellite. As before, the risk of collision $\mu^* = \mu(\lambda^*, q^*, r^*)$ is taken as given, resulting from the other firms' behavior λ^* , q^* and r^* . Also, we let s^* denote the equilibrium price of removal certificates.

Compared to the open access, the satellite operator now additionally pays the ad valorem tax τ on the cash-flow of its satellite and the launch tax l at launch. It also have to purchase ε removal certificates at price s^* . The (regulated) operator thus anticipates the following *expected* net present value of a marginal satellite:

$$\frac{(1 - \tau)p}{\delta + \lambda + \mu^*} - c(\lambda) - l - s^* \varepsilon. \quad (2.14)$$

Using the same steps as in section 2.4, the operators' behaviors will be characterized by the conditions:²²

$$-\frac{p}{(\delta + \lambda^* + \mu^*)^2} - c'(\lambda^*) = -\frac{\tau p}{(\delta + \lambda^* + \mu^*)^2} \quad (2.15)$$

and

$$\frac{p}{\delta + \lambda^* + \mu^*} - c(\lambda^*) = \frac{\tau p}{\delta + \lambda^* + \mu^*} + l + s^* \varepsilon. \quad (2.16)$$

Consider now the market for removal effort certificates. Removal firms incur a cost d per unit of effort r . In return, they are granted an equivalent number of certificates, which they

²²Clearly, we find equation (2.5), (2.6) and (2.7) as a special case when $l = \tau = 0$.

supply on the market at price s^* . Their profit is thus:

$$(s^* - d) r.$$

Clearly, they have an incentive to increase (resp., decrease) their supply r whenever $s^* > d$ (resp., $s^* < d$). Besides, satellite operators demand εq^* certificates to meet their obligation. It follows that a market equilibrium satisfies:

$$s^* = d \tag{2.17}$$

and

$$r^* = \varepsilon q^*. \tag{2.18}$$

Below, we will refer to the following:

Proposition 4. Under regulation, the physico-economic equilibrium λ^* , q^* and r^* , together with the equilibrium price s^* , satisfies conditions (2.15) to (2.18) .

We calculate in appendix A2 the associated comparative statics. Our results are summarized here:

Proposition 5. Assume that $\varepsilon > 0$ and $\mu_q^* + \varepsilon\mu_r^* > 0$. The regulated equilibrium λ^* , q^* and r^* satisfies:²³

- (i) The planned lifetime $1/\lambda^*$ does not depend on δ , is increasing in d , τ and l , and decreasing in p ;
- (ii) The launch rate q^* and removal effort r^* are decreasing in δ , d , τ and l , and increasing in p .

The comparative statics with respect to δ and p are the same as for the open access equilibrium and the same insights hold here. An increase in d has the same effect as an increase in l , within a factor of proportionality. We thus only comment on the policy instruments. We begin with the ad valorem tax τ . Note that it is the only instruments appearing in (2.15), meaning that only the ad valorem tax influences λ^* directly. Other things equal, it provides an incentive to shorten the satellites' planned lifetime. Proposition 5 states the opposite, due to indirect effects on q^* and r^* . Indeed, by making satellites less profitable, a larger τ induces a smaller launch rate q^* and removal effort r^* .²⁴ In the long run, assuming that $\mu_q^* + \varepsilon\mu_r^* > 0$, these changes induce a smaller collision risk μ^* . As this favors the design of more durable satellites, Proposition 5 actually proves that these indirect effects are dominant. Consider now the launch tax l . Its introduction reduces the *expected* net present value of a marginal

²³If $\mu_q^* + \varepsilon\mu_r^* < 0$, part (i) of the proposition is unchanged, while part (ii) is reversed.

²⁴Remember that they vary proportionally, as $r^* = \varepsilon q^*$.

satellite. This provides a direct incentive to reduce the launch rate q^* and the removal effort r^* . When $\mu_q^* + \varepsilon\mu_r^* > 0$, a smaller risk of collision μ^* results in the long run, inducing in turn the satellite operator to design more durable satellites (i.e., smaller λ^*).

Consider finally the obligation to hold ε removal effort certificates per satellite. The direct motivation is to increase removal efforts. However, this has indirect consequences. First of all, the cost of purchasing certificates makes satellites less profitable. The satellite operators want to reduce q^* and r^* . Assuming that $\mu_q^* + \varepsilon\mu_r^* > 0$, this induces a decrease of the long run risk of collision μ^* , pushing in turn the satellite operators to design more durable satellites. Overall, these intricated interactions make the comparative statics with respect to ε ambiguous.

The incentive instruments l , τ and ε are said to implement the optimal policy if $\lambda^* = \lambda^o$, $q^* = q^o$ and $r^* = r^o$. We show that this happens if:

$$\tau^o = -\mu_\lambda^o, \quad (2.19)$$

$$l^o = \left(\mu_\lambda^o + \frac{\mu_q^o q^o + \mu_r^o r^o}{\delta + \lambda^o + \mu^o} \right) \frac{p}{\delta + \lambda^o + \mu^o}, \quad (2.20)$$

and

$$\varepsilon^o = r^o/q^o. \quad (2.21)$$

Indeed, substituting these expressions and assuming that $\lambda^* = \lambda^o$, $q^* = q^o$ and $r^* = r^o$, conditions (see (2.15) to (2.18)) simplify to:

$$\begin{aligned} -\frac{p}{(\delta + \lambda^o + \mu^o)^2} - c'(\lambda^o) &= \frac{\mu_\lambda^o p}{(\delta + \lambda^o + \mu^o)^2}, \\ \frac{p}{\delta + \lambda^o + \mu^o} - c(\lambda^o) &= \frac{\mu_q^o p q^o}{(\delta + \lambda^o + \mu^o)^2}, \\ d &\geq -\frac{\mu_r^o p q^o}{(\delta + \lambda^o + \mu^o)^2}, \end{aligned}$$

with the last condition satisfied as an equality whenever $r^o > 0$. We know that these equations characterize the optimal policy λ^o , q^o and r^o (see (2.11) to (2.13)).

These formulas deserve some comments. The ad valorem tax τ^o is between 0 and 100 percent under assumption 1 and assumption (ii) of proposition 3. However, the launch tax l^o , which one expects positive, can be negative if:

$$-\mu_\lambda^o > \frac{\mu_q^o + \varepsilon^o \mu_r^o}{\delta + \lambda^o + \mu^o} q^o.$$

This happens either when $\mu_q^o + \varepsilon^o \mu_r^o \leq 0$ or when $\mu_q^o + \varepsilon^o \mu_r^o > 0$ and $-\mu_\lambda^o$ is large enough. In

the first case, increasing of q^o and r^o proportionally reduces μ^o . In the second case, increasing of q^o and r^o proportionally increases μ^o , but is compensated by a larger λ^o . In both cases, a negative launch tax is understandable, as the scale of space activity can be expanded with less risk of collision.

2.7 Numerical illustration

We specify and calibrate our model to match real data. We perform a sensitivity analysis with respect to the unit cost of removal effort, as these technologies are currently in the exploratory stage.

The specification of the risk of collision is based on the physical model in appendix A1, using simplifying assumptions explained in appendix A4:

$$\mu(\lambda, q, r) = \frac{1}{2} \left(\frac{\theta_{\underline{\beta}}^{\eta} (\bar{\alpha} + 1) q - \bar{\beta} - r - \lambda}{+\sqrt{\left(\theta_{\underline{\beta}}^{\eta} (\bar{\alpha} + 1) q - \bar{\beta} - r + \lambda\right)^2 + 4(\bar{\beta} + r - \rho\lambda) \theta_{\underline{\beta}}^{\eta} q}} \right),$$

where $\bar{\alpha}$, $\underline{\beta}$, $\bar{\beta}$, η and θ are physical parameters.²⁵

For all $\lambda > \underline{\lambda}$, we specify the cost function as:

$$c(\lambda) = a + \left(\frac{b}{\lambda - \underline{\lambda}} \right)^{\sigma},$$

where a , b , $\underline{\lambda}$ and σ are positive parameters.²⁶ The lowest cost possible is a , for a very short planned lifetime (as $c(\lambda) \rightarrow a$ for $\lambda \rightarrow \infty$). The ratio $1/\underline{\lambda}$ is the longest technically and/or economically possible planned lifetime (as $c(\lambda) \rightarrow \infty$ for $\lambda \rightarrow \underline{\lambda}$).

Our calibration of the economic parameters relies on the following data. The total revenue of the satellite manufacturers and launchers was \$17,400 million in 2019 (SIA, 2020) and \$16,500 million in 2020 (SIA, 2021). According to the UCS database (UCS, 2021), the number of satellites launched was 262 in 2019, out of a total of 312, and 1,156 in 2020, out of a total of 1,184. This gives an estimate of the unit cost of satellites, of an order of \$15.8 million/sat. for low Earth orbits and of \$42.9 million/sat for higher altitudes.²⁷ Besides, in 2020, the total revenue from satellite services was \$117,800 million (SIA, 2021). With a fleet of 3,392 commercial satellites in activity (UCS, 2021), this yields an average revenue of \$26.3 million/sat. However, we argue that this average is an overestimate for low Earth orbit, which we therefore adjust by assuming the same margin rate at all altitudes. After correction, the order of magnitude is \$22.1 million/sat. in low Earth orbit. A typical satellite

²⁵See appendix A4 for the derivation and A5 for the calibration.

²⁶This implicitly implies that $\bar{\lambda} = \infty$.

²⁷In accordance with our physical model, we normalized the units by considering satellites of mass equal to 500 kg.

in low Earth orbit has a planned lifetime of 4.65 years (UCS, 2021). Finally, we use a discount rate of 5 % a year.

Our benchmark calibration is summarized in Table 2.1.²⁸ Given the lack data, parameter d will be subjected to a sensitivity analysis. Our results are displayed in Tables 2.2 and Figure 2.2.

Coefficient	Estimate	Unit	Sources
a	7.9	\$/sat.	SIA (2021) & UCS (2021)
b	0.2352	/	Conjectured
$1/\lambda$	25	y.	UCS (2021)
σ	7	/	Conjectured
p	22.1	\$/sat./y.	SIA (2021) & UCS (2021)
δ	5	%/y.	Conjectured
d	[1500 – 3500]	(\$/y.)/(1/y.)	Sensitivity analysis

Table 2.1: Benchmark Calibration

Consider first the simulation for $d = 2,500$ (\$/y.)/(1/y.).²⁹

Table 2.2 summarizes the most relevant results. Under open access, the satellite operators launch $q^* = 1006$ satellites per year, each with a planned lifetime of $1/\lambda^* = 2.82$ years. Due to a probability $P^* = 87$ % of collision during their mission, their operational lifetime drops to $1/(\lambda^* + \mu^*) = 0.37$ years. The steady state fleet size is $S^* = 372$ satellites. In the optimal policy, the satellite operators launch $q^o = 136$ satellites per year with a planned lifetime of $1/\lambda^o = 3.86$ years. The removal effort is $r^o = 53$ %/year, so that inactive objects are removed on average $1/r^o = 2.61$ years after their mission ends. The probability of a satellite being destroyed during its mission is $P^o = 32$ %, so its operational lifetime is reduced to $1/(\lambda^o + \mu^o) = 2.61$ years. The steady state size of the fleet is $S^o = 354$ satellites.

	Planned lifetime (years)	Launch (sat./y.)	Removal effort (%/y.)	Risk of collision (%)	Actual lifetime (years)	Fleet (sat.)	Net revenue (\$/y.)
Open access	2.82	1006	0	87	0.37	372	0
Optimum	3.86	136	53	32	2.61	354	4,294
Ad val. & launch taxes	3.34	224	0	64	1.26	288	3,978
Removal certificates	3.38	499	196	74	0.86	431	0

Table 2.2: Equilibrium and optimal outcomes

²⁸The data collected and calibration steps are explained in a supplementary document.

²⁹Recall that this is the cost of removing 63 % of current inactive objects in one year. At the end of 2021, with a population of approximately 4000 objects, the unit cost of removing one of them would be $2,500/(0.63 \times 4000) = 1$ \$/sat.

We also calculated the economic instruments implementing an optimal policy (i.e., τ^o , l^o and ε^o satisfying (2.19) to (2.21)). We find an ad valorem tax $\tau^o = 55.9\%$, a launch tax $l^o = 3.14$ \$million/sat., and a removal effort $\varepsilon^o = 0.39\%$ /year/sat. Overall, the satellite operators would pay annually \$4,373.13 million in ad valorem tax, \$425.75 million in launch tax, and \$1333.79 million in removal certificates.

The last two rows of Table 2.2 consider simulations where fiscal (ad valorem and launch taxes) and market (removal certificates) instruments would be used separately, bearing in mind that an international agreement on the latter would perhaps be easier to obtain. Compared to the optimal policy, only using fiscal instruments would lead to launching more satellites (224 satellites per year, instead of 136 satellites per year) and decreasing their designed lifetime (3.34 years, instead of 3.86 years). In addition, the absence of removal effort would cause both the satellite operational lifetime (1.26 years, instead of 2.61 years) and fleet (282 satellites, instead of 354 satellites) to decline sharply. Overall, the net revenue would decrease from \$4.294 million to \$3.978 million. On the other hand, only using the market instrument would lead to a sharp acceleration in the satellite launches (499 satellites per year, instead of 136 satellites per year), each designed for a shorter lifetime (3.38 years, instead of 3.86 years). The lack of fiscal incentives, amplified by an increased removal effort (196 %/year, instead of 53%/year), would create a rebound effect, as documented by the increase of the satellite fleet (431 satellites, instead of 354 satellites). Ultimately, the only merit of this scenario would be to support the removal industry, which would absorb the surplus generated by the satellite services market, leaving no net revenue.

We finally propose a sensitivity analysis, varying d between 1,500 and 3,500 (\$m/yr.)/(1/y.). Our results are presented in Figure 2.2. The orange curves represent the open access equilibrium. The blue curves represent the optimal policy.

We comment the most important lessons in the following stylized facts:

Fact 1. At the open access equilibrium, the satellites' planned lifetime is always too short (Fig2.2.a) and the launch rate always too large (Fig2.2.b) compared with the optimal policy.

Fact 2. The optimal effort to remove inactive satellites is decreasing in d , before it becomes null beyond 3,150 (\$m/y.)/(1/y.) (Fig2.2.c). As long as a removal effort is profitable, the optimal planned lifetime is first increasing in d , until $d \simeq 2,445$ (\$m/y.)/(1/y.), and then decreasing for larger values (Fig2.2.a). The optimal launch rate is first decreasing as d increases, until $d \simeq 1,340$ (\$m/y.)/(1/y.), and then increasing for larger values (Fig2.2.b).

Fact 2 deserves an explanation. It is expected that the optimal removal effort decreases with its cost. Adjustments to the other decisions follow. All other things equal, less removal effort, by increasing the risk of collision, pushes to manufacture less durable satellites and to slow down launches. In turn, these changes modify the collision risk, this time downward, and

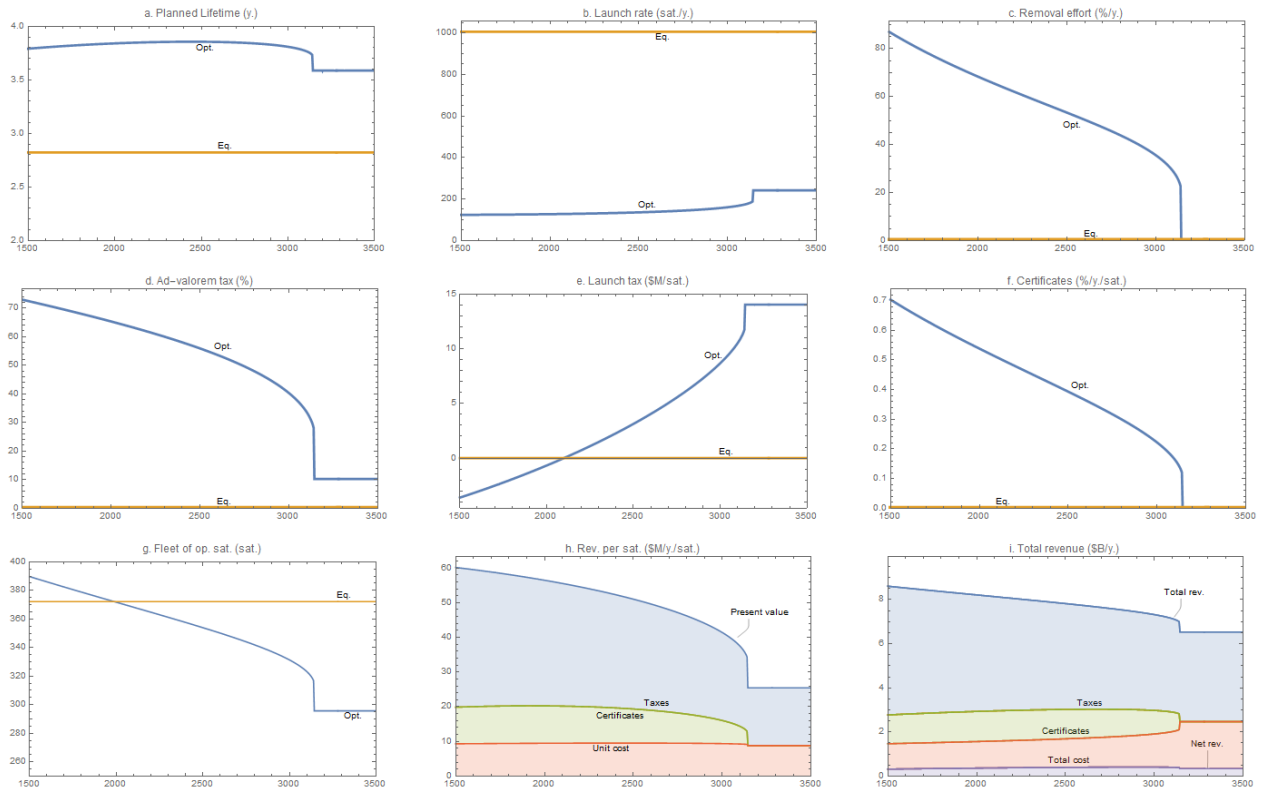


Figure 2.2: Sensitivity analysis ($1,500 \leq d \leq 3,500$)

initiate second-order adjustments. Moreover, the manufacture of less durable, and therefore less expensive, satellites restores their profitability. In the end, the outcome depends on the relative magnitude of these many interactions. Fact 2 shows three successive responses as d increases. For d less than 1,340 ($\$/\text{y.})/(1/\text{y.})$, it is optimal to extend the planned lifetime of satellites, but to slow down launches. For d between 1,340 ($\$/\text{y.})/(1/\text{y.})$ and 2,445 ($\$/\text{y.})/(1/\text{y.})$, in addition to extending their planned lifetime, it becomes optimal to accelerate launches. For d greater than 2,445 ($\$/\text{y.})/(1/\text{y.})$, the optimal behavior becomes to decrease the planned lifetime and to launch more. In all cases, the overall result is to maintain a smaller and smaller satellite fleet as d increases (Fig2.2.g).

Fact 3. The number of removal certificates per launched satellite is decreasing in d , before it becomes null beyond 3,150 ($\$/\text{y.})/(1/\text{y.})$ (Fig2.2.f). As long as certificates are required, the ad valorem tax is decreasing and the launch tax is increasing in d . The launch tax is negative for a unit cost of removal effort less than $d \simeq 2,100$ ($\$/\text{y.})/(1/\text{y.})$.

To understand Fact 3, remember that the ad valorem and launch taxes have different purposes. The former provides an incentive to design satellites with a shorter lifetime. When inactive objects are quickly removed, this makes sense as most collisions happen during the operational lifetime. The launch tax influences launches by affecting the profitability of satellites. However, the two taxes are substitutable in this respect, because the ad valorem tax also affects the profitability of satellites. Once put in perspective with Fact 2, these

insights explain why the ad valorem tax is large and the launch tax is negative for small costs of the removal effort.

Fig2.2.h breaks down the expected present value of a marginal satellite into its different components. The part in blue pays the ad valorem and launch taxes. The part in green funds the purchase of removal certificates. The part in red represents the cost of a satellite. By definition, there is no surplus left to the space sector. In fact, the net present value generated by the space sector is collected by the regulator through the ad valorem and launch taxes.

Fig2.2.i decomposes instead the aggregate flow of revenue generated by the fleet of satellites. Again, the part in blue pays the ad valorem and launch taxes. The part in green is used to purchase the removal certificates. The part in red reflects the cost of renewing decayed satellites. Here, the sum of previous components leaves an operating surplus, figured in purple, counterpart of the rental value of the satellite fleet.

2.8 Strategic behaviors

Most economic literature on the satellite industry assumes perfect competition and atom-icity of the economic agents.³⁰ However, the ongoing deployment of mega-constellations of satellites makes this issue increasingly sensitive. In this section, we propose an extension of our framework to show how strategic behaviors might alter our conclusions. All results are based on numerical simulations.³¹

From here on, we consider an industry made up of n identical satellite operators, indexed by $i = 1, \dots, n$. Each firm i 's plan is given by λ_i , q_i and r_i , giving the failure rate and launch rate of its satellites, and its cleaning effort. As before, we focus on the long-run steady state of the orbital environment. In doing so, we implicitly assume that firms are committed to adopting a constant strategy forever.

If all firms choose the same failure rate (i.e., $\lambda_i = \lambda$ for all i), it can be shown that the long-term collision risk is unchanged from the previous section (see appendix A4). Formally, it can then be written as $\mu(\lambda, q, r)$, where we let $\lambda = \sum_{i=1}^n \lambda_i/n$, $q = \sum_{i=1}^n q_i$ and $r = \sum_{i=1}^n r_i$. When the failure rates vary from one firm to another, the calculation of the steady state becomes untractable. However, as we restrict our attention below to symmetric Cournot equilibria, we can use the same specification as an approximation, which is justified by the continuity of the steady state in the vicinity of these equilibria.

³⁰There are only four exceptions (Adilov, Alexander and Cunningham, 2015, Bernhard, Deschamps and Zaccour, 2023, Klima, 2016, 2018), but they are not relevant to our problem. Adilov, Alexander and Cunningham (2015) considers a limited horizon (two periods) and focus on Geosynchronous Earth Orbit. Bernhard, Deschamps and Zaccour (2023) supplies a dynamic duopoly game, but must assume that an international “active debris removal agency” keeps the stock of debris constant at an exogenous level to calculate the (Markovian Nash) equilibrium of the game. Klima (2016, 2018) is irrelevant because the demand side of the market is ignored in these papers.

³¹The details are explained in a supplementary document.

The consumers' preferences are represented by their maximum willingness to pay $W(S)$ for satellite services generated by a fleet of size S (see equation (2.3)). Subsequently, we will also need to define the inverse demand function $P(S) = W'(S)$ and average willingness to pay $w(S) = W(S)/S$.

The objective of each firm i is to choose a strategy λ_i , q_i and r_i to maximize the net present value of the satellites it launches:

$$\left(\frac{P(z)}{\delta + \lambda_i + \mu(\lambda, q, r)} - c(\lambda_i) \right) q_i - dr_i,$$

where $S = q/(\lambda + \mu(\lambda, q, r))$. A symmetric Cournot equilibrium is defined as a strategy profile λ^* , q^* and r^* , such that each firm i maximizes its objective by playing $\lambda_i = \lambda^*$, $q_i = q^*$ and $r_i = r^*$, given that its competitors play $\lambda_j = \lambda^*$, $q_j = q^*$ and $r_j = r^*$, for all $j \neq i$.

In this setting, the social objective is defined as a plan maximizing the aggregate net present value that the space sector periodically generates:

$$\pi_i = \left(\frac{w(S)}{\delta + \lambda + \mu} - c(\lambda) \right) q - dr,$$

where $S = q/(\lambda + \mu(\lambda, q, r))$.

In our simulation, we specify the maximum willingness to pay as:

$$W(S) = (A - BS/2)S,$$

where A and B are positive parameters.³² Given the limited information available on the demand for satellite services, the calibration of parameters A and B will be purely illustrative. However, it will be chosen to match the results of the previous section. Calibration of the other parameters is unchanged (see Table 2.1).

³²Note that this setting is equivalent to that of Section 2.7 in the special case where $A = p$ and $B = 0$.

	Planned lifetime (years)	Launch (sat./y.)	Removal effort (%/y.)	Risk of colli- sion (%)	Actual lifetime (years)	Fleet (sat.)	Loss of welfare (%)
Monopoly	3.69	161	25	48	1.93	310	2.35
Duopoly	3.11	531	0	79	0.65	345	20.54
Oligopoly ($n = 3$)	2.99	679	0	82	0.53	357	35.7
Oligopoly ($n = 5$)	2.92	806	0	85	0.45	364	50.09
Oligopoly ($n = 25$)	2.84	965	0	86	0.38	371	69.21
Oligopoly ($n = 100$)	2.83	995	0	87	0.37	372	72.96
Perfect competition	2.82	1006	0	87	0.37	372	74.23
Optimum	3.86	152	50	39	2.31	354	/

Table 2.3: Equilibrium and optimal outcomes ($A = 30$ and $B = 0.021$)

Table 2.3 shows the simulation results for the benchmark calibration where $A = 30$ (\$m/sat./y.) and $B = 0.021$ (\$m/sat.²/y.). To begin with, we note that Fact 1 remains true, although it is attenuated when strategic behaviors are taken into account. As their number increases, firms are encouraged to launch more satellites (from 161 to 1006 satellites per year) with shorter lifetimes (from 3.69 to 2.82 years). Note that the Cournot equilibrium tends towards the open-access physico-economic equilibrium determined previously for a very large number of firms (see Table 2.2).

Beyond the confirmation of Fact 1, this simulation allows us to add the following stylized facts:

Fact 4. Provided it is highly concentrated, the satellite industry may have an interest in cleaning up the orbital environment. Nevertheless, its debris removal effort is always too small compared to the optimal policy.

With our benchmark calibration ($d = 2,500$ (\$m/y.)/(1/y.)), only a monopoly firm makes a debris removal effort. Sensitivity analyses show that this result holds true as long as the unit cost of debris removal exceeds 600 (\$m/yr.)/(1/y.). By definition of the Cournot equilibrium, firms anticipate the long-term effects of their decisions on the orbital environment. They therefore have an interest in limiting the proliferation of debris. However, this incentive is counterbalanced by the fact that their effort to remove debris benefits the industry as a whole. This is not just a classic public good problem, whereby satellite operators under-invest in orbit cleaning because they only receive a fraction of the benefits (proportional to the size of their satellite fleet). Another reason for a satellite operator to refrain from orbit depollution is that, in the long term, it increases the size of the satellite fleets in operation, both one's own and those of others, thereby reducing the equilibrium market price. Our simulations show that these effects are strong enough to discourage any debris removal efforts as soon

as firms are competing with a few competitors. In the case of a monopoly, the same reason pushes the monopoly to under-invest in orbit cleaning expenditure, with a removal effort of 25 %/year only, instead of 50 %/year for an optimal policy.

Fact 5. The size of the operating satellite fleet and the loss of social surplus increases with the number of actors in the market.

This fact implies that increased competition worsens the situation in the satellite market and in the orbital environment. Two opposing forces contribute to this. On the one hand, market power drives firms to limit the size of their satellite fleet, in order to support the long-term equilibrium price of satellite services. On the other hand, the incentive to free ride leads them to design and launch too many satellites with too short a lifespan, and to neglect orbit depollution. As the number of companies on the market increases, the first force, initially dominant, is gradually overtaken by the second. Thus, compared to the optimal policy (354 satellites), the total fleet of operating satellites (from 310 and 372 satellites), initially undersized in the case of a monopoly and a duopoly, becomes oversized beyond. Finally, from the point of view of the present value social surplus generated, our simulations show that the firms' choices are always detrimental and more and more costly as their number increases. Welfare loss ranges from 2.35 % in the case of a monopoly to 74.23 % in the case of perfect competition.

2.9 Conclusion

In this article, we have presented a physico-economic model of low Earth orbit exploitation, assuming that the space sector makes choices regarding the design and launch of satellites, and the removal effort. Focusing on the long-term sustainability, we have compared the equilibrium behaviors under open access with an optimal allocation. We have shown how to use economic instruments to guide private behaviors toward an optimal policy. Finally, simulations have been carried based on a realistic calibration.

Future research should be conducted in several directions. First, more detailed economic data should be collected on the satellite sector. More advanced integrated models, including several orbital layers and a more refined typology of space objects, would allow more operational recommendations to be made. Some technological innovations, such as debris detection or in-orbit satellite repair and refueling, should be studied.

2.10 Annexes

Annex A1. Physical model

We propose a physical model based on Farinella and Cordelli (1991), Laffeur (2011), Percy (2015) and Rouillon (2020). It is composed of three differential equations, one for

debris fragments, another one for rocket bodies and end-of-life satellites and the last one for active satellites. The extensions of Rouillon (2020) are the consideration of the (natural and active) decay of inactive objects and the re-entry of satellites at the end of their mission.

We formalize the evolution of the orbital environment with the following dynamical system:

$$\begin{cases} \dot{x}(t) = \underline{\alpha}q(t) + \underline{s}(t) - \underline{\beta}x(t) + \eta\theta x(t)(y(t) + z(t)), & x(0) = x_0 \\ \dot{y}(t) = \bar{\alpha}q(t) + \bar{s}(t) - (\bar{\beta} + r(t))y(t) + (1 - \rho)\lambda(t)z(t) - \theta x(t)y(t), & y(0) = y_0 \\ \dot{z}(t) = q(t) - (\lambda(t) + \theta x(t))z(t), & z(0) = z_0 \end{cases}$$

The first differential equation describes the evolution of the population of debris fragments, $x(t)$. The first term, $\underline{\alpha}q(t)$, refers to fragments released as a by-product of satellite launches (i.e., explosion of rocket bodies and space objects), with $\underline{\alpha} > 0$ their number per satellite launched $q(t)$. The second term, $\underline{s}(t)$, reflects pieces of debris coming from nearby altitudes. Inversely, the third term, $\underline{\beta}x(t)$, represents the decay of debris fragments due to the atmospheric drag, with $\underline{\beta} > 0$ the inverse of their average orbital lifetime. The last term, $\eta\theta x(t)(y(t) + z(t))$, gives the addition of debris fragments generated by collisions of debris fragments with intact objects, with $\eta > 0$ their numbers per collision and $\theta x(t) \geq 0$ the rate of collision per satellite.

The second differential equation formalizes the evolution of the population of rocket bodies and inactive satellites, $y(t)$. The first component, $\bar{\alpha}q(t)$, represents rocket upper stages released by launching activities, with $\bar{\alpha} > 0$ their number per satellite launched. The second term, $\bar{s}(t)$, is the additional inactive satellites from the upper altitudes. The third term, $(\bar{\beta} + r(t))y(t)$, represents the decay of the stock of big objects, due to either the atmospheric drag, with $\bar{\beta} > 0$ the inverse of their natural average orbital lifetime, or to removal efforts, with $r(t) \geq 0$ the inverse of the average duration before an inactive objects is removed.³³ The term, $\lambda(t)z(t)$, represents operational satellites arriving at the end of their mission, with $\lambda(t) > 0$ the inverse of their average designed lifetime. Among these, only $(1 - \rho)\lambda(t)z(t)$ remain in orbit, with $\rho \in [0, 1]$ the fraction of re-entry. The last term, $\theta x(t)y(t)$, refers to inactive satellites destroyed by collisions.

The last differential equation gives the evolution of the population of operational satellites, $z(t)$. The first component, $q(t)$, is the result of the launch activity. The second term, $(\lambda(t) + \theta x(t))z(t)$, refers to the number of satellites that cease to operate, either for technical (i.e., failures) or environmental reasons (i.e., collisions).

³³Drawing on the standard bioeconomic model, we implicitly consider here a removal production function $AE(t)y(t)$, where A is a catchability coefficient, $E(t)$ is the fleet of cleaning spacecrafts and $y(t)$ is the population of inactive objects. In our paper, we define the rate of removal $r(t) = AE(t)$ to save notation.

Let us consider a constant space activity forever, i.e., $\lambda(t) = \lambda$, $q(t) = q$ and $r(t) = r$ for all t . Assuming that the nearby altitudes are in a stationary state, implying that $\underline{s}(t) = \underline{s}$ and $\bar{s}(t) = \bar{s}$ for all t , we analyse the steady states of the dynamical system, i.e., $x(t) = x^*$, $y(t) = y^*$ and $z(t) = z^*$ satisfying:

$$\dot{x}(t) = \underline{\alpha}q + \underline{s} - \underline{\beta}x^* + \eta\theta x^*(y^* + z^*) = 0,$$

$$\dot{y}(t) = \bar{\alpha}q + \bar{s} - (\bar{\beta} + r)y^* + (1 - \rho)\lambda z^* - \theta x^* y^* = 0,$$

$$\dot{z}(t) = q - (\lambda + \theta x^*)z^* = 0.$$

Because an explicit solution is cumbersome (i.e., cubic equation), we characterize it analytically by deriving its comparative statics. The linearized system is:

$$A \begin{pmatrix} \mathbf{d}x^* \\ \mathbf{d}y^* \\ \mathbf{d}z^* \end{pmatrix} = \begin{pmatrix} -\underline{\alpha}\mathbf{d}q \\ -(1 - \rho)z^*\mathbf{d}\lambda - \bar{\alpha}\mathbf{d}q + y^*\mathbf{d}r \\ z^*\mathbf{d}\lambda - \mathbf{d}q \end{pmatrix},$$

where:

$$A = \begin{pmatrix} \eta\theta(y^* + z^*) - \underline{\beta} & \eta\theta x^* & \eta\theta x^* \\ -\theta y^* & -\bar{\beta} - r - \theta x^* & (1 - \rho)\lambda \\ -\theta z^* & 0 & -\lambda - \theta x^* \end{pmatrix}.$$

We calculate that:

$$\det(A) = \frac{-\left(\underline{\beta} - \eta\theta(y^* + z^*)\right) (\bar{\beta} + r + \theta x^*) (\lambda + \theta x^*)}{-\eta\theta^2 x^* \left((\lambda + \theta x^*) y^* + ((1 - \rho)\lambda + \bar{\beta} + r + \theta x^*) z^*\right)} < 0.$$

We verify that $\det(A) < 0$ because $\dot{x}(t) = 0$ implies that $(\underline{\beta} - \eta\theta(y^* + z^*))x^* = \underline{\alpha}q + \underline{s} \geq 0$.

We then show that:

$$\mathbf{d}x^* = \frac{1}{\det(A)} \begin{pmatrix} (\bar{\beta} + r + \rho\theta x^*) \eta\theta x^* z^* \mathbf{d}\lambda \\ - \left(\begin{array}{c} \underline{\alpha}(\bar{\beta} + r + \theta x^*) (\lambda + \theta x^*) \\ +\eta\theta x^* ((\bar{\beta} + r + \theta x^*) + \bar{\alpha}(\lambda + \theta x^*) + (1 - \rho)\lambda) \\ +\eta\theta x^* (\lambda + \theta x^*) y^* \mathbf{d}r \end{array} \right) \mathbf{d}q \end{pmatrix},$$

$$\mathbf{d}y^* = \frac{1}{\det(A)} \begin{pmatrix} - \left(\begin{array}{c} -((1 - \rho)\underline{\beta} + \rho\eta\theta y^*) \theta x^* z^* \mathbf{d}\lambda \\ (\underline{\beta} - \eta\theta(y^* + z^*)) (\bar{\alpha}(\lambda + \theta x^*) + (1 - \rho)\lambda) \\ -\underline{\alpha}\theta((\lambda + \theta x^*) y^* + (1 - \rho)\lambda z^*) \\ -\eta\theta^2 x^* (y^* - \bar{\alpha}z^*) \end{array} \right) \mathbf{d}q \\ + \left((\underline{\beta} - \eta\theta(y^* + z^*)) (\lambda + \theta x^*) + \eta\theta^2 x^* z^* \right) \mathbf{d}r \end{pmatrix},$$

$$\mathbf{d}z^* = \frac{1}{\det(A)} \begin{pmatrix} \left(\begin{array}{c} (\underline{\beta} - \eta\theta(y^* + z^*))(\bar{\beta} + r + \theta x^*) \\ + \eta\theta^2 x^*(y^* + (1 - \rho)z^*) \end{array} \right) z^* \mathbf{d}\lambda \\ - \left(\begin{array}{c} (\underline{\beta} - \eta\theta(y^* + z^*))(\bar{\beta} + r + \theta x^*) \\ + \eta\theta^2 x^*(y^* - \bar{\alpha}z^*) \\ - \underline{\alpha}(\bar{\beta} + r + \theta x^*)\theta z^* \\ - \eta\theta^2 x^* y^* z^* \mathbf{d}r \end{array} \right) \mathbf{d}q \end{pmatrix}.$$

Since $\underline{\beta} - \eta\theta(y^* + z^*) \geq 0$ and $\det(A) < 0$, this implies that:

- x^* is decreasing in λ and r , and increasing in q ;
- y^* is decreasing in r and increasing in λ ;
- z^* is decreasing in λ and increasing r .

The steady state rate of collision θx^* corresponds to $\mu(\lambda, q, r)$ in the main text. These results thus justifies assumption 1 (comparative statics of x^*) and assumption (ii) in proposition 4 (comparative statics of $z^* = q/(\lambda + \theta x^*)$). We can also verify assumption (i) of proposition 4 if \underline{s} and \bar{s} are negligible.

We finally investigate the local stability of the steady state. A necessary and sufficient condition is for matrix A to have all its eigenvalues with negative real part. The corresponding characteristic polynomial is:

$$\det(A - \nu I) = -(\nu + \lambda + \theta x^*) \left(\begin{array}{c} \nu^2 + (\underline{\beta} - \eta\theta(y^* + z^*) + \bar{\beta} + r + \theta x^*)\nu \\ + (\underline{\beta}\theta x^* + (\bar{\beta} + r)(\underline{\beta} - \eta\theta(y^* + z^*))) \end{array} \right) - \eta\theta^2 x^* z^* (\bar{\beta} + r - \rho\lambda).$$

In the special case where $\eta\theta^2 x^* z^* (\bar{\beta} + r - \rho\lambda) = 0$, the eigenvalues are:

$$\begin{aligned} \nu_1 &= -\lambda - \theta x^*, \\ \nu_2 &= \frac{1}{2} \left(\begin{array}{c} -(\underline{\beta} - \eta\theta(y^* + z^*) + \bar{\beta} + r + \theta x^*) \\ + \sqrt{(\underline{\beta} - \eta\theta(y^* + z^*) + \bar{\beta} + r + \theta x^*)^2 - 4(\underline{\beta}\theta x^* + (\bar{\beta} + r)(\underline{\beta} - \eta\theta(y^* + z^*)))} \end{array} \right), \\ \nu_3 &= \frac{1}{2} \left(\begin{array}{c} -(\underline{\beta} - \eta\theta(y^* + z^*) + \bar{\beta} + r + \theta x^*) \\ - \sqrt{(\underline{\beta} - \eta\theta(y^* + z^*) + \bar{\beta} + r + \theta x^*)^2 - 4(\underline{\beta}\theta x^* + (\bar{\beta} + r)(\underline{\beta} - \eta\theta(y^* + z^*)))} \end{array} \right). \end{aligned}$$

Given that $\underline{\beta} - \eta\theta(y^* + z^*) \geq 0$, all have negative real parts. By continuity, this will hold in the general case if $\eta\theta^2 x^* z^* (\bar{\beta} + r - \rho\lambda)$ is small enough.

Annex A2. Comparative statics

The open access and regulated equilibria satisfy:³⁴

$$-\frac{(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} - c'(\lambda^*) = 0,$$

$$\frac{(1-\tau)p}{\delta+\lambda^*+\mu^*} - c(\lambda^*) = l + d\varepsilon,$$

and

$$\varepsilon q^* - r^* = 0,$$

with $\mu^* = \mu(\lambda^*, q^*, r^*)$.

By differentiation, we derive the linearized system:

$$\begin{pmatrix} \frac{2(1+\mu_\lambda^*)(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*) & \frac{2\mu_q^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} & \frac{2\mu_r^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} \\ -\frac{(1+\mu_\lambda^*)(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} - c'(\lambda^*) & -\frac{\mu_q^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} & -\frac{\mu_r^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} \\ 0 & \varepsilon & -1 \end{pmatrix} \begin{pmatrix} d\lambda^* \\ dq^* \\ dr^* \end{pmatrix} \\ = \begin{pmatrix} -\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} d\delta + \frac{(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} \frac{dp}{p} - \frac{(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} \frac{d\tau}{1-\tau} \\ \frac{(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} d\delta + \varepsilon dd + dd\varepsilon + dl - \frac{(1-\tau)p}{\delta+\lambda^*+\mu^*} \frac{dp}{p} + \frac{(1-\tau)p}{\delta+\lambda^*+\mu^*} \frac{d\tau}{1-\tau} \\ -q^* d\varepsilon \end{pmatrix}.$$

We then triangulate it:

$$\begin{pmatrix} \frac{2(1+\mu_\lambda^*)(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*) & \frac{2\mu_q^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} & \frac{2\mu_r^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} \\ \frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*) & 0 & 0 \\ 0 & \varepsilon & -1 \end{pmatrix} \begin{pmatrix} d\lambda^* \\ dq^* \\ dr^* \end{pmatrix} \\ = \begin{pmatrix} -\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} d\delta + \frac{(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} \left(\frac{dp}{p} - \frac{d\tau}{1-\tau} \right) \\ \frac{2d\varepsilon}{\delta+\lambda^*+\mu^*} \left(\frac{dd}{d} + \frac{d\varepsilon}{\varepsilon} \right) + \frac{2}{\delta+\lambda^*+\mu^*} dl - \frac{(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} \left(\frac{dp}{p} - \frac{d\tau}{1-\tau} \right) \\ -q^* d\varepsilon \end{pmatrix}.$$

We can then show:

$$d\lambda^* = \frac{\frac{2}{\delta+\lambda^*+\mu^*} (\varepsilon dd + dd\varepsilon) + \frac{2}{\delta+\lambda^*+\mu^*} dl - \frac{(1-\tau)p}{(\delta+\lambda^*+\mu^*)^2} \left(\frac{dp}{p} - \frac{d\tau}{1-\tau} \right)}{\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*)},$$

³⁴The open access equilibrium corresponds to the particular case where $l = \tau = \varepsilon = 0$.

$$\mathbf{dq}^* = \frac{1}{\mu_q^* + \varepsilon\mu_r^*} \begin{pmatrix} -\mathbf{d}\delta - \frac{(\delta+\lambda^*+\mu^*)^2}{(1-\tau)p} \left(1 + \frac{\frac{2\mu_\lambda^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3}}{\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*)} \right) (\varepsilon\mathbf{d}d + \mathbf{d}l) \\ - \left(\frac{(\delta+\lambda^*+\mu^*)^2}{(1-\tau)p} \left(1 + \frac{\frac{2\mu_\lambda^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3}}{\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*)} \right) d + \mu_r^* q^* \right) \mathbf{d}\varepsilon \\ + (\delta + \lambda^* + \mu^*) \left(1 + \frac{\frac{\mu_\lambda^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3}}{\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*)} \right) \left(\frac{\mathbf{d}p}{p} - \frac{\mathbf{d}\tau}{1-\tau} \right) \end{pmatrix}$$

and

$$\mathbf{dr}^* = \frac{\varepsilon}{\mu_q^* + \varepsilon\mu_r^*} \begin{pmatrix} -\mathbf{d}\delta - \frac{(\delta+\lambda^*+\mu^*)^2}{(1-\tau)p} \left(1 + \frac{\frac{2\mu_\lambda^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3}}{\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*)} \right) (\varepsilon\mathbf{d}d + \mathbf{d}l) \\ - \left(\frac{(\delta+\lambda^*+\mu^*)^2}{(1-\tau)p} \left(1 + \frac{\frac{2\mu_\lambda^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3}}{\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*)} \right) d + \mu_r^* q^* \right) \mathbf{d}\varepsilon \\ + (\delta + \lambda^* + \mu^*) \left(1 + \frac{\frac{\mu_\lambda^*(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3}}{\frac{2(1-\tau)p}{(\delta+\lambda^*+\mu^*)^3} - c''(\lambda^*)} \right) \left(\frac{\mathbf{d}p}{p} - \frac{\mathbf{d}\tau}{1-\tau} \right) \end{pmatrix} + q^* \mathbf{d}\varepsilon.$$

Knowing that $\mu_\lambda < 0$, $\mu_q > 0$, $\mu_r < 0$ (assumption 1) and $2p/(\delta + \lambda^* + \mu^*)^3 - c''(\lambda^*) < 0$ (second order condition), the comparative statics for λ^* can be disambiguated:

- λ^* does not depend on δ , is decreasing in d , ε , l and τ , and increasing in p .

The comparative statics for q^* and r^* depends on the sign of $\mu_q^* + \varepsilon\mu_r^*$, because their proportional variations ($r^* = \varepsilon q^*$) have opposite effect on μ^* . If $\mu_q^* + \varepsilon\mu_r^* > 0$, our results show that:³⁵

- q^* and r^* are decreasing in δ , d , l and τ , and increasing in p .

Finally note that the comparative statics with respect to ε are ambiguous.

Annex A3. Proof of Proposition 4

An optimal policy λ^o , q^o and r^o satisfies:

$$\left(\frac{p}{\delta + \lambda^o + \mu(\lambda^o, q^o, r^o)} - c(\lambda^o) \right) q^o - dr^o \geq \left(\frac{p}{\delta + \lambda + \mu(\lambda, q, r)} - c(\lambda) \right) - dr,$$

for all feasible λ , q and r .

³⁵All results are reversed if $\mu_q^* + \varepsilon\mu_r^* < 0$.

We first prove that $\underline{\lambda} < \lambda^o < \bar{\lambda}$. Indeed, the derivative of the social objective with respect to λ , evaluated at the optimal policy, is:

$$\left(-\frac{(1 + \mu_\lambda^o) p}{(\delta + \lambda^o + \mu^o)^2} - c'(\lambda^o) \right) q^o.$$

If $q^o > 0$, it is:

- positive if $\lambda^o \rightarrow \underline{\lambda}$, as $\lim_{\lambda^o \rightarrow \underline{\lambda}} (-c'(\lambda^o)) = \infty$ by assumption 1;
- negative when $\lambda^o \rightarrow \bar{\lambda}$, as $1 + \mu_\lambda^o > 0$ by condition (ii) of proposition 4 and $\lim_{\lambda^o \rightarrow \bar{\lambda}} (-c'(\lambda^o)) = 0$ by assumption 1.

We now show that $q^o > 0$. By contradiction, if we let $q^o = 0$, we have:

$$\left(\frac{p}{\delta + \lambda^o + \mu(\lambda^o, q^o, r^o)} - c(\lambda^o) \right) q^o = 0.$$

Assuming that:

- there exists $\underline{\lambda} < \lambda < \bar{\lambda}$ such that $p/(\delta + \lambda) - c(\lambda) > 0$;
- $\mu(\lambda, q, r)$ is negligible for small enough q ;

we can find λ and q such that:

$$\left(\frac{p}{\delta + \lambda + \mu(\lambda, q, r^o)} - c(\lambda) \right) q > 0.$$

This yields a contradiction since:

$$\left(\frac{p}{\delta + \lambda + \mu(\lambda, q, r^o)} - c(\lambda) \right) - dr^o > \left(\frac{p}{\delta + \lambda^o + \mu(\lambda^o, q^o, r^o)} - c(\lambda^o) \right) q^o - dr^o.$$

Annex A4. Specification of $\mu(\lambda, q, r)$

Consider the physical model of annex A1. Assuming that $\underline{\alpha} = \underline{s} = \bar{s} = 0$, a steady state must satisfy:

$$\dot{x}(t) = -\underline{\beta}x^* + \eta\theta x^*(y^* + z^*) = 0,$$

$$\dot{y}(t) = \bar{\alpha}q - (\bar{\beta} + r)y^* + (1 - \rho)\lambda z^* - \theta x^* y^* = 0,$$

$$\dot{z}(t) = q - (\lambda + \theta x^*)z^* = 0.$$

The first and last equations imply that (assuming that $x^* > 0$):

$$y^* = \frac{\underline{\beta}}{\eta\theta} - \frac{q}{\lambda + \theta x^*}$$

and:

$$z^* = \frac{q}{\lambda + \theta x^*}.$$

After substitution in the second equation, we derive the second degree equation:

$$(x^*)^2 - \left(\frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \frac{\bar{\beta} + r}{\theta} - \frac{\lambda}{\theta} \right) x^* - \left(\left(\frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \frac{\bar{\beta} + r}{\theta} \right) \frac{\lambda}{\theta} + \frac{\eta}{\underline{\beta}} \left(\frac{\bar{\beta} + r}{\theta} - \rho \frac{\lambda}{\theta} \right) q \right) = 0.$$

If

$$q \geq \frac{\beta \lambda}{\eta \theta},$$

it admits only one positive root:

$$x^* = \frac{1}{2} \left(\frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \frac{\bar{\beta} + r}{\theta} - \frac{\lambda}{\theta} + \sqrt{\left(\frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \frac{\bar{\beta} + r}{\theta} + \frac{\lambda}{\theta} \right)^2 + 4 \frac{\eta}{\underline{\beta}} \left(\frac{\bar{\beta} + r}{\theta} - \rho \frac{\lambda}{\theta} \right) q} \right).$$

The steady state risk of collision is:

$$\mu^* \equiv \theta x^* = \frac{1}{2} \left(\theta \frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \bar{\beta} - r - \lambda + \sqrt{\left(\theta \frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \bar{\beta} - r + \lambda \right)^2 + 4\theta \frac{\eta}{\underline{\beta}}(\bar{\beta} + r - \rho\lambda)q} \right).$$

Its derivatives are:

$$\frac{\partial \mu^*}{\partial \lambda} = \frac{1}{2} \frac{\theta \frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \bar{\beta} - r + \lambda - \sqrt{\left(\theta \frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \bar{\beta} - r + \lambda \right)^2 + 4\theta \frac{\eta}{\underline{\beta}}(\bar{\beta} + r - \rho\lambda)q - 2\theta \frac{\eta}{\underline{\beta}}\rho q}}{\sqrt{\left(\theta \frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \bar{\beta} - r + \lambda \right)^2 + 4\theta \frac{\eta}{\underline{\beta}}(\bar{\beta} + r - \rho\lambda)q}} < 0,$$

$$\frac{\partial \mu^*}{\partial q} = \theta \frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1) \frac{\lambda + \mu^* + \frac{\bar{\beta} + r - \rho\lambda}{\bar{\alpha} + 1}}{\sqrt{\left(\theta \frac{\eta}{\underline{\beta}}(\bar{\alpha} + 1)q - \bar{\beta} - r + \lambda \right)^2 + 4\theta \frac{\eta}{\underline{\beta}}(\bar{\beta} + r - \rho\lambda)q}} > 0,$$

and

$$\frac{\partial \mu^*}{\partial r} = - \frac{\lambda + \mu^* - \theta \frac{\eta}{\underline{\beta}} q}{\sqrt{\left(\theta \frac{\eta}{\underline{\beta}} (\bar{\alpha} + 1) q - \bar{\beta} - r + \lambda\right)^2 + 4\theta \frac{\eta}{\underline{\beta}} (\bar{\beta} + r - \rho \lambda) q}} < 0.$$

Annex A5. Calibration of the physical model

Table 2.4 compares our calibration with Farinella and Cordelli (1991), Laffleur (2011) and Percy (2015).

Coefficient	Farinella & Cordelli (1991)	Laffleur (2011)	Percy (2015)	This paper	Units
$\underline{\alpha}$	70	70	38.06	/	frag./sat.
$1/\underline{\beta}$	/	184.9	7,022.7	1,000	year
$\bar{\alpha}$	/	/	/	0.2	r.b./sat.
$1/\bar{\beta}$	/	14,420	7,938	10,000	year
η	10,000	10,000	169.5	5,000	frag./sat.
$1/\lambda$	/	/	10 or 20	4.65	year
θ	3×10^{-10}	6.895×10^{-10}	4.54×10^{-10}	4×10^{-10}	1/year/sat.
q	100	31.41	70.9	83	sat./year
ρ	/	/	0.7	0.25	/
x_0	50,000	110,400	313,377.8	1,000,000	frag.
$y_0 + z_0$	2,000	4,650	2,644	4,000	sat.

Table 2.4: Benchmark calibrations

Figure 2.3.a and 2.3.b plots the evolution of the populations of debris fragments and big objects using the harmonized scenario in table 2.5, starting in 2020 with the average launch rate of years 2014-2018. Beyond differences during the transition dynamics, attributable to the different calibrations, we verify that all models tend to converge in the long run.

Coefficient	Orbital state & exploitation rate	Source
x_0	1,000,000	ESA (2022)
$y_0 + z_0$	8,000	ESA (2022) & UCS (2022)
q	210	SIA (2019)

Table 2.5: Harmonized scenario

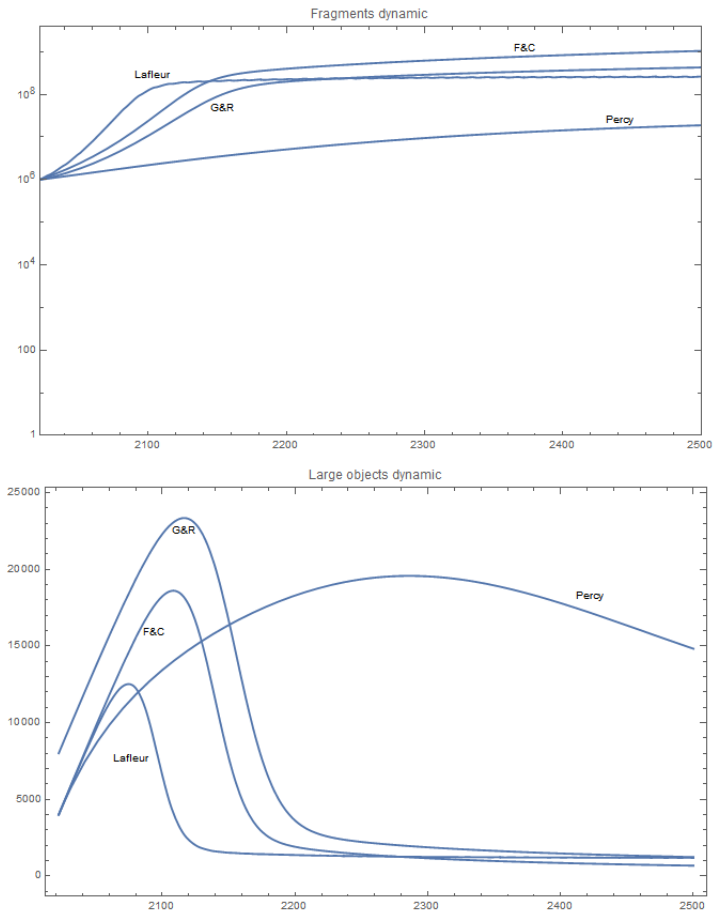


Figure 2.3: Comparisons (units: year, log. fragments; year, objects)

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Chapter 3

A layered model of the long-run orbit use economics

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Abstract

This paper follows the work initiated by Rouillon (2020) on the long-run use of the orbit. Satellite operators choose an altitude layer to operate their satellites and design them accordingly. In the long run, a given launch policy leads to an equilibrium for the whole layered model. We compare the launch rates per layer and the resulting orbital state for two management regimes. The open access equilibrium occurs in the absence of regulation. The optimal policy maximizes the net present value generated periodically by the satellite industry. We show that a launch tax has to be differentiated by the chosen altitude of operation in order to efficiently regulate the orbit use. A numerical application using a realistic calibration illustrates these results.

Keywords: Space economics, orbital debris, sustainability, satellites.

3.1 Introduction

Some regions of Low Earth Orbit (LEO) are currently subject to the plans for several new large constellations. This reinforces some already existing concerns about space debris. For some time, new economics approaches have been developed to study this issue and to provide some insights regarding space policy. As other economic activities, the satellite industry creates some negative externalities. The reduction of the lifespan of satellites through collisions has already been estimated to amount to roughly \$100 million in 2020 (Adilov et al, 2023). As the number of space debris in orbit increases, the question of the long-run sustainability arises. This article aims to contribute to a better understanding of this issue.

In 1978, a paper from Kessler and Cour-Palais showed that the overuse of Earth orbit could result in a catastrophic chain of collisions that would make the orbit unusable in the long-term, known as the Kessler Syndrome. Four decades later, another paper (Adilov, Alexander and Cunningham, 2018) showed that the orbit could become economically unprofitable before this happens. Recently, some researchers started to use the tools of economics to design some regulatory frameworks dealing with these issues (Adilov, Alexander and Cunningham, 2015 and 2020, Béal, Deschamps and Moulin, 2020, Bernhard, Deschamps and Zaccour, 2023, Grzelka and Wagner, 2019, Guyot and Rouillon, 2023, Macauley, 2015, Rao, Burgess and Kaffine, 2020, Rouillon, 2020). Economic instruments such as a launch tax (Adilov, Alexander and Cunningham, 2015, Béal, Deschamps and Moulin, 2020, Rouillon, 2020) or an orbit-use tax (Rao, Burgess and Kaffine, 2020) could prevent an overuse of orbit that would threaten the sustainability of the satellite industry. Additionally, these instruments can correctly internalize the external costs of collisions. Once the cost of collisions is accounted for, satellite operators would be incentivised to optimally use the orbit. In the absence of economics instruments or remediation tools, Nozawa et al. (2023) estimated that the negative externality of space debris would represent approximately 1.95% of global Gross Domestic Product (GDP) in the long-run.

This paper extends the work of Rouillon (2020), which proposed an analysis focusing on low Earth orbit taken as a whole. In this new work, we propose a new layered model that allows to endogenize the operating altitude of satellites. Satellite operators choose the layer's altitude at which their satellites will be operated. The cost of a satellite varies with its altitude of operation. In addition, the physical specifics of each layer will influence the environmental externality that satellites will exert on each other. The endogeneity of altitude choices also introduces an asymmetry. Fragments generated in a layer will gradually fall back to Earth, endangering satellites operating in the lower layers.

Methodologically, the approach is identical to that of Rouillon (2020). We analyse the long-term equilibrium of the orbit. We assume a constant launch rate maintained in each layer in the long-run. This paper considers two regimes of orbit management. First, the

open access equilibrium that would result from the private interests of satellite operators in the absence of regulation. In this situation, satellite owners neglect the externalities for which they are responsible when they launch and operate their satellites. Second, the optimal policy that maximizes the value produced periodically by the orbital activity. Under open access, the space sector launching policy is suboptimal, since they neglect their own impact on collision risks. As a result, operators launch too many satellites in some layers. We show that a launch tax must be differentiated by layers' altitude to incentivize satellite operators to implement the optimal launch policy.

This paper is organized as follows. Section 2 describes the layered model. Section 3 characterizes its open access physico-economic equilibrium. Section 4 derives the optimal policy. Section 5 proposes economic instruments to regulate space activity. In Section 6, consists in a numerical application. Supplementary materials and proofs are supplied in an appendix.

3.2 The model

Consider the space activity in low Earth orbit,¹ divided in N layers of altitudes. The highest one to be potentially used is layer 1. Assume that the space sector continuously launches q_i satellites per period depending on layer i , $i \in [1, N]$.² The altitude considered for a layer i is its median altitude h_i .³ Furthermore, the time during which a satellite will be able to provide a service will depends on both technical (i.e., fuel exhaustion, components failure) and environmental (i.e., collisions) events. On the one hand, the rate of defect by technical failure λ is assumed to be exogenous. On the other hand, the rate of collision μ_i is directly linked to the space activity, and thus endogenous. On collision, satellites disintegrate, releasing η fragments in the orbital layer. In the absence of such an event, at the end of their mission, defect satellites remaining in orbit fall back to Earth naturally, going through layers, unless they are actively removed in the meantime.

We propose a stylized layered physical model of low Earth orbit, based on Farinella and Cordelli (1991), Lafleur (2011), Percy (2015) and Rouillon (2020). Each layer state is modelled by three differential equations, one for the population of debris fragments, another one for big remnants of space operations (i.e., inactive satellites) and the last one for active satellites. Big objects (rocket bodies, end-of-life and active satellites) typically have a cross-

¹Low Earth orbit is the region of space that encompasses altitudes between 200 and 2,000 km. We focus on this orbital region because of two facts. First, because it is already very crowded with space debris. Second, because this region is the one that is subject to the biggest launch plans thanks to its closeness to the Earth. We also exclude medium and geostationary orbits because the physical and economic heterogeneity between orbital regions (i.e., decay rate, launch cost, satellite design) would affect the quality of our results.

²Satellites characteristics might differ in many respects (mass, surface, power, etc.). In our model, we consider a representative satellite unit, following Guyot and Rouillon (2023).

³For example, if layer 1 is considered to be the layer that includes all altitudes from 1900 to 2000 km, it will be defined by an altitude $h_i = 1950$ km.

section of a few square meters and a mass of hundreds of kilograms. Debris fragments are small objects generated by collisions or explosions, of sufficient size to cause catastrophic breakup when impacting a big object.

We use the following notations, for any given layer i :

$q_i(t)$ = rate of active satellites launched;

$x_i(t)$ = population of debris fragments;

$y_i(t)$ = population of inactive satellites;

$z_i(t)$ = population of active satellites.

Layer 1 will be the highest layer to be used. Layer 0 will be considered to be all higher altitudes that are assumed to be empty, i.e. $x_0(t) = y_0(t) = z_0(t) = 0$.⁴

We formalize the evolution of the orbital environment with the following dynamical system:

$$\begin{cases} \dot{x}_i(t) = \underline{\alpha}q_i(t) + \beta_{i-1}x_{i-1}(t) - \beta_i x_i(t) + \eta\theta_i x_i(t)(y_i(t) + z_i(t)), & x_i(0) = x_{i,0} \\ \dot{y}_i(t) = \bar{\alpha}q_i(t) + \lambda z_i(t) - \theta_i x_i(t)y_i(t), & y_i(0) = y_{i,0} \\ \dot{z}_i(t) = q_i(t) - (\lambda + \theta_i x_i(t))z_i(t), & z_i(0) = z_{i,0} \end{cases}$$

The first differential equation describes the evolution of the population of debris fragments, $x_i(t)$. The first term, $\underline{\alpha}q_i(t)$, refers to fragments released as a by-product of satellite launches (i.e., explosion of rocket bodies and space objects), with $\underline{\alpha} > 0$ the number of fragments per satellite launched. The second term, $\beta_{i-1}x_{i-1}(t)$, reflects pieces of debris coming from nearby altitudes, decayed by the atmospheric drag. Inversely, the third term, $\beta_i x_i(t)$, represents the decay of the stock of debris fragments due to the atmospheric drag, with $\beta_i > 0$ the inverse of their average orbital lifetime. The last term, $\eta\theta_i x_i(t)y_i(t)$, is the amount of debris fragments generated by collisions of debris fragments with inactive satellites, with $\eta > 0$ the numbers of fragments per collision and $\theta_i x_i \geq 0$ the rate of collision per unit of satellite.

The second differential equation represents the evolution of the population of rocket bodies and inactive satellites, $y_i(t)$. The first component, $\bar{\alpha}q_i(t)$, represents rocket upper stages released by launching activities, with $\bar{\alpha} > 0$ their number per satellite launched. The term $\lambda z_i(t)$, represents operational satellites arriving at the end of their mission, thus becoming inactive by technical failure, with $\lambda > 0$ the inverse of their average designed lifetime. The last term, $\theta_i x_i(t)y_i(t)$, refers to the number of inactive satellites destroyed as a result of collisions.

⁴Layer 0 is the layer of altitudes over 2000 km (i.e., over low Earth orbit). We assume that satellites in MEO and GEO will have a negligible effect on the LEO environment because of their small number. Consequently, it is assumed that layer 1 will not receive debris from this upper layer.

The last differential equation gives the evolution of the population of operational satellites, $z_i(t)$. The first component, $q_i(t)$, is the result of the launch activity by the space sector. The second term, $(\lambda + \theta_i(t)x_i(t))z_i(t)$, refers to the number of satellites that cease to operate, either for technical reasons (i.e., fuel exhaustion, failures) or environmental reasons (i.e., collisions).

The present model omits two components of the orbit dynamics that are big objects decay and collisions between inactive satellites. These have been left over for the sake of formal resolution.

The long-run steady state

Following Rouillon (2020), we focus on the long-run equilibrium of the orbital environment. In the present layered model, this equilibrium will be resulting from an assumed launch rate settings q_1, q_i, \dots, q_N being kept constant in every shells.

In Appendix A1, we calculate the long-run steady state of the environment. We show that the long-run debris fragments stock, inactive satellites stock and the active satellites stock of a given layer i respectively write

$$x_i^* = \frac{1}{\beta_i} ((\underline{\alpha} + \eta\bar{\alpha} + \eta) q_i + \beta_{i-1}x_{i-1}^*), \quad (3.1)$$

$$y_i^* = \frac{(1 + \bar{\alpha}) q_i}{\theta_i x_i^*} - z_i^*, \quad (3.2)$$

and

$$z_i^* = \frac{q_i}{\lambda + \theta_i x_i^*}. \quad (3.3)$$

The first equation is worth some explanations. $\underline{\alpha}$, $\bar{\alpha}$ and η are parameters that depends on the satellites and launching technologies. Their sum is the potential number of fragments related to one satellite placed into orbit. To simplify, big objects are assumed to stay in orbit indefinitely. Consequently, in the long run, the yearly launch of a satellite unit will generate a yearly flux of $\underline{\alpha} + \eta\bar{\alpha} + \eta$ fragments into the layer. The addition of fragments coming from the upper layer $i - 1$ gives the complete yearly influx of fragments in layer i . A proportion β_i of these debris fragments will decay each year. After accounting for it, we obtain equation (3.1).

Note that the flux of fragments coming from any layer writes

$$\beta_i x_i^* = (\underline{\alpha} + \eta\bar{\alpha} + \eta) q_i + \beta_{i-1} x_{i-1}^*,$$

that is the addition of the fragments debris that are generated in this layer on the one hand, and the number of fragments coming from the upper one on the other. Using this

simple recurrence relation, one can reformulate equation (3.1) such that the stock of debris fragments in a layer only depends on the sum of all launch rates from layer i to the highest one (layer 0):

$$x_i^* = \frac{1}{\beta_i} \left((\underline{\alpha} + \eta \bar{\alpha} + \eta) \sum_{j=0}^{j=i} q_j \right). \quad (3.4)$$

The rate of collision induced by a single fragment in layer i is θ_i . The rate of collision in a given layer thus writes:

$$\mu_i^* = \mu_i \left(\sum_{j=0}^{j=i} q_j \right) = \frac{\theta_i}{\beta_i} (\underline{\alpha} + \eta \bar{\alpha} + \eta) \sum_{j=0}^{j=i} q_j. \quad (3.5)$$

Economic parameters and assumptions

The economic parameters are the following. The cost to design, manufacture, and launch a satellite operated on a layer of altitude h_i is $c_i(h_i)$. That will be abbreviated in c_i for notational convenience. The periodic revenue perceived from the flow of service from one satellite is p .⁵ The economic agents are assumed to discount time at the rate of time preference δ .

From now on, we will also assume the following:

Assumption 1. The cost to put a satellite in orbit is convex, first decreasing and then increasing. Figure 3.1 illustrates a possible cost function and both components contained in it. On the one hand, as embedded fuel and motorization power needed to counter the drag from the residual atmosphere diminishes with altitude, the cost to manufacture a satellite is assumed to diminish accordingly (Figure 3.1.a). On the other hand, the cost to launch a satellite increases with altitude, as the required rocket has to be more powerful and carry more fuel (Figure 3.1.b). It is assumed that the decreasing manufacturing costs first dominates as altitude grows. Then, at some point, the overall cost starts to increase with altitude, as the increasing launch cost surpasses the lowering manufacturing cost (Figure 3.1.c).

3.3 Open access equilibrium

In this section, we investigate the private incentives of the space sector to operate a given layer when the orbit is freely accessible. By definition, open access means that the number of satellite operators can vary, through entries or exits. No regulation is implemented. Moreover, satellite operators are not liable for the objects they leave in orbit and therefore have no obligation to clean the orbit. Satellite operators are free to send as many satellites

⁵Following Rouillon (2020) and Guyot and Rouillon (2023), we assume a perfectly competitive market for satellite services.

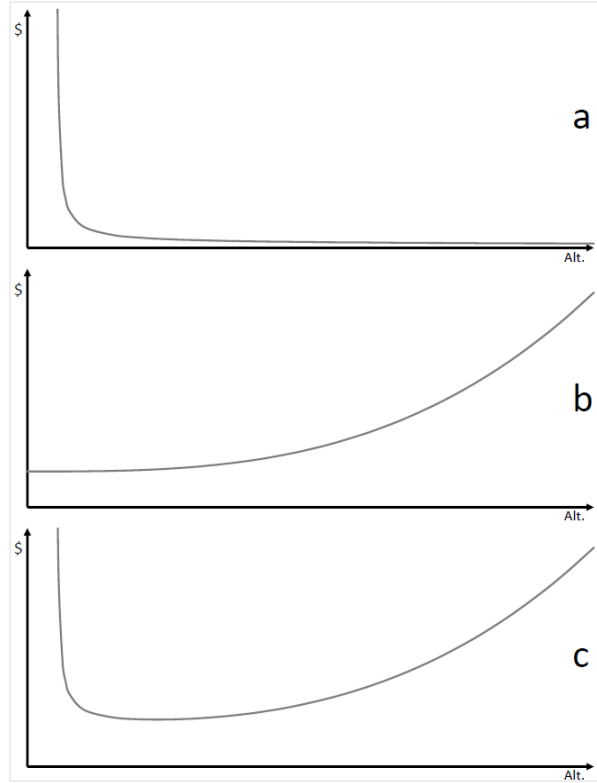


Figure 3.1: Figure (a) illustrates a cost of countering the atmospheric drag decreasing with altitude. Figure (b) illustrates a launch cost increasing with altitude. Figure (c) aggregates both costs, leading to satellite cost function first increasing and then decreasing.

as they wish. Presumably, they will do so as long as they can expect a positive net present value per satellite launched.

In order to represent the objectives of satellite operators, assume that the orbital environment is in its long run stationary state, resulting from the other firms' behaviour. Thus, the risk of collision is $\mu_i^* = \mu_i \left(\sum_{j=0}^{j=i} q_j^* \right)$, where q_j^* stands for their launch decisions in the current layer and all the above ones.

The *expected* present value of a satellite is:⁶

$$\frac{p}{\delta + \lambda + \mu_i^*}. \quad (3.6)$$

Satellite operators launching a satellite bears an immediate cost c_i . They have an incentive to launch more satellites as long as they obtain a positive net present value per satellite. Therefore, they will be satisfied with their strategy if and only if the launch rate q_i^* satisfies:

$$\left(\frac{p}{\delta + \lambda + \mu_i^*} - c_i \right) q_i^* = 0. \quad (3.7)$$

In other words, the overall present value of the fleet in orbit must be null. There are two

⁶See Guyot and Rouillon (2023) for the calculation.

possibilities. If $p/(\delta + \lambda + \mu_i^*) - c_i < 0$, it is not profitable to launch a satellite in the layer.⁷ Otherwise, satellite operators will launch satellites until the present value of a satellite (i.e., $p/(\delta + \lambda + \mu_i^*)$) becomes equal to its unit cost (i.e., c_i).

We summarize our ideas in the following:

Definition 1. A physico-economic equilibrium refers to allocations $q_1^*, q_i^*, \dots, q_N^*$ that satellite operators would implement to maximize their own profits.

Proposition 1. Under open access, a physico-economic equilibrium must satisfy condition (3.7).

Starting again from equation 3.7, one can write the equilibrium as a condition on the rate of collision. There are two cases that can be expressed as follows

$$\begin{cases} \mu_i^* = \frac{p}{c_i} - (\delta + \lambda) & \text{if } \frac{p}{\delta + \lambda + \mu_i \left(\sum_{j=0}^{i-1} q_j \right)} - c_i > 0 \\ \mu_i^* = \mu_i \left(\sum_{j=0}^{i-1} q_j \right) & \text{otherwise.} \end{cases}$$

Again, two cases are possible. The first case covers the situation where a layer i can still be profitable once the long-run stock of debris fragments derived from the above layers is accounted for. In this situation, the aggregate launch rate of satellite operators at this altitude will be set such that the collision rate is high enough for the *expected* present value of a satellite to be null. The second case covers the situation where the collision rate induced by fragments falling from the higher layers already make this layer unprofitable. In this case, the collision rate might be higher.

By substituting μ_i^* by its expression calculated with our physical model, we can express the open access equilibrium launch rate for any layer i as follows:

$$\begin{cases} q_i^* = \frac{1}{\alpha + \eta\bar{\alpha} + \eta} \frac{\beta_i}{\theta_i} \left(\frac{p}{c_i} - (\delta + \lambda) \right) - \sum_{j=0}^{i-1} q_j. & \text{if } \frac{p}{\delta + \lambda + \mu_i \left(\sum_{j=0}^{i-1} q_j \right)} - c_i > 0 \\ q_i^* = 0. & \text{otherwise.} \end{cases}$$

From this equation, it appears straightforwardly that if the condition of profitability of a layer is fulfilled, then

- There is a maximal long-run launch rate equilibrium in open access in any layer i , that would occur if none of the upper layers would be used, amounting to $\frac{1}{\alpha + \eta\bar{\alpha} + \eta} \frac{\beta_i}{\theta_i} \left(\frac{p}{c_i} - (\delta + \lambda) \right)$.

⁷This can happen because (a) $p/(\delta + \lambda) - c_i < 0$, meaning that even in a perfectly clean environment, a satellite is too costly to be profitable, or (b), when $p/(\delta + \lambda + \mu_i \left(\sum_{j=0}^{i-1} q_j \right)) - c_i < 0$, meaning that too much debris come from the upper layers for a satellite to operate long enough to be profitable.

- The long-run launch rate equilibrium in open access in any layer i will be lowered by the exact amount of launches happening in the higher layers from the maximal value.

3.4 Optimal policy

In the long run, the space sector periodically generates an aggregate net present value equal to:

$$\sum_{i=1}^N \left(\frac{p}{\delta + \lambda + \mu_i} - c_i \right) q_i, \quad (3.8)$$

where the risk of collision $\mu_i = \mu_i \left(\sum_{j=0}^{j=i} q_j \right)$ is now seen as endogenous.

Below, our postulate will be that the social objective should be to maximize (3.8). We will refer to the following:

Definition 2. An optimal policy refers to allocations $q_1^o, q_i^o, \dots, q_N^o$ that maximize the yearly net present value of space activity (3.8) subject to the constraint $q_i \geq 0$.

Again, there are two possibilities. The first one is that the maximizing strategy consists to not launch any satellite in the layer, i.e., $q_i^* = 0$. This might happen because:

1. The cost to put a satellite at this altitude is too high, even in the absence of externality, i.e., $p / (\delta + \lambda) - c_i < 0$.
2. Above layers offer such a profitability that the collision rate induced by the optimal use of the above layers is too high for this layer to be profitable, i.e., $p / \left(\delta + \lambda + \mu_i \left(\sum_{j=0}^{j=i-1} q_j^o \right) \right) - c_i < 0$.
3. The negative external cost that it would impose at this altitude and the below ones is bigger than the expected revenue of a marginal satellite. i.e., $p / (\delta + \lambda + \mu_i^o) - c_i < \sum_{j=i}^N \left(\partial \mu_j^o / \partial q_i^o \right) / (\delta + \lambda + \mu_j^o)^2 p_j q_j^o$.

The second possibility is that it is optimal to launch satellites in the layer, i.e. an interior solution. Then, optimal launch rate must solve the following first order condition:

$$\frac{p}{\delta + \lambda + \mu_i^o} = c_i + \sum_{j=i}^N \frac{\partial \mu_j^o / \partial q_i^o}{(\delta + \lambda + \mu_j^o)^2} p_j q_j^o, \quad (3.9)$$

meaning that, in the long run, the actual value of a satellite must be equal to its cost plus the sum of externalities that it will generate in this layer and on all the lower ones.

3.5 Regulation

In our model, the discrepancy between the open-access equilibrium and the optimal policy arises from the external effects of space sector launching choices on the collision risk. In this section, we describe how to regulate the activity of the space sector by applying a launch tax that would internalize this externality. The aim is to find the tax values that would correctly incentivize the firms to launch the optimal number of satellites.⁸

Consider the launch rate q_i in layer i . The operators gain by launching more as long as the net present value of a marginal satellite is positive. Since each satellite sent in orbit is a potential reservoir of future debris, a launch will induce a social cost in the long run. From equation (3.9), the satellite operators should be charged $\sum_{j=i}^N \frac{\partial \mu_j^o / \partial q_i^o}{(\delta + \lambda_j + \mu_j^o)^2} p_j q_j^o$ per satellite to internalize it. This social cost encompasses the economic burden on layer i and on all the lower ones. Below, this externality will be addressed by a launch tax l_i paid at the time of launch.

We analyse below the behaviour of the space sector subject to this regulatory framework. We first express the physico-economic equilibrium that is characterized by the choices of satellite operators.

Let us first proceed to update the calculus of the *expected* net present value of a marginal satellite in a layer i . As before, the risk of collision $\mu^* = \mu_i \left(\sum_{j=0}^{j=i} q_j^* \right)$ is taken as given, resulting from the other firms' in this layer and all the above ones.

Compared to the open access, the satellite operator now additionally pays the launch tax l_i at launch. The (regulated) satellite operators will anticipate the (updated) present value *expected* profit of a marginal satellite:⁹

$$\frac{p}{\delta + \lambda + \mu_i^*} - c_i - l_i. \quad (3.10)$$

meaning that the value of the tax should be set such that sending more satellites than what is optimal would not be economically profitable. In other words, the tax must equal the marginal value of a satellite at the optimal launch rate.

⁸In the short term, the collective adoption of an international treaty that is required to implement an optimal regulation is unlikely in the short term. Still, studying the optimal regulation can improve our understanding of the issue of space debris.

⁹The open access expression in Section 3.3 appears as a special case when $l_i = 0$.

In the long-run, the physico-economic equilibrium writes:

$$\frac{p}{\delta + \lambda + \mu_i^*} - c_i = l_i. \quad (3.11)$$

Below, we will refer to the following:

Proposition 2. Under regulation, the physico-economic equilibrium refers to allocations $q_1^*, q_i^*, \dots, q_N^*$ that satisfies condition (3.11).

The introduction of a launch tax l_i reduces the *expected* net present value of a marginal satellite. This provides a direct incentive to reduce the launch rate q_i^* in the layer.

The incentive instrument l_i will implement the optimal policy if it leads to a physico-equilibrium such that $q^* = q^o$. By identification, we show that this happens if:

$$l_i^o = \sum_{j=i}^N \frac{\partial \mu_j^o / \partial q_i^o}{(\delta + \lambda_j + \mu_j^o)^2} p_j q_j^o, \quad (3.12)$$

i.e., the optimal tax must be equal to the sum of the externalities caused by a satellite in a layer and all the lower ones.¹⁰

Indeed, substituting this expression and assuming $q^* = q^o$ condition (see (3.11)) simplifies to:

$$\frac{p}{\delta + \lambda + \mu_i^o} - c_i = \sum_{j=i}^N \frac{\partial \mu_j^o / \partial q_i^o}{(\delta + \lambda + \mu_j^o)^2} p_j q_j^o.$$

We have shown previously that this equation characterizes the optimal policy q_i^o for any given layer i (see (3.9)).

3.6 Numerical illustration

We present the results of our model specified and calibrated to match real data. Then, given the lack of accurate data regarding the satellite industry economics, we conduct a sensitivity analysis over the satellite revenue.

The model encompasses all of low Earth orbit, with $N = 18$ layers of 100 km of altitudes each, going from 200 km to 2000 km. The calibration of the physical model is presented in Appendix A2.

¹⁰This condition ensures that satellite operators will correctly be incentivized to launch the optimal number of satellites. But in cases where the optimal situation consists to not launch any satellite in a given layer, lower tax rates could be enough to disincentivize them to launch satellites. For example, that would be the case if a layer is already unprofitable in the absence of a tax. The necessary condition for any launch tax to be optimal is that the marginal value of a first launch minus its launch tax should be negative, i.e., $p/(\delta + \lambda + \mu_i^*) - c_i - l_i < 0$.

Cost function

We specify the cost function as:

$$c_i = c(h_i) = a - bh_i + \frac{d}{2}h_i^2,$$

where a , b and d are positive parameters. $c(h_i)$ is a convex function. It first decreases until it reaches a minimal cost of $a - \frac{1}{2}\frac{b^2}{d}$ for an altitude of $h_i = b/d$. Above this threshold, it increases with altitude.

We assume a constant rate of failure such that $\lambda = 1/4$ for all i , leading to a planned lifetime of 4 years for every satellites. Other physical characteristics of satellites¹¹ are described in Appendix A2.

Our benchmark calibration of economic parameters is summarized in Table 3.1.

Coefficient	Estimate	Unit	Sources
a	100	$\$/sat.$	Conjectured
b	0.15	$\$/km/sat.$	Conjectured
d	0.00015	$\$/km^2/sat.$	Conjectured
p	22.1	$\$/sat./y.$	Guyot and Rouillon (2023)
δ	5	$\%/y.$	Conjectured

Table 3.1: Benchmark Calibration

Numerical results

Table 3.2 and 3.3 summarize the most relevant results. The stability of the equilibria are discussed in Appendix A4.

¹¹We consider normalized satellites units of mass equal to 500 kg.

Layer index i	Layer's altitude range (km)	Opt. launch tax (\$m/sat.)	Launch rate (sat./y.)		Collision probability (%)		Operational lifetime (years)		Fleet (sat.)	
			Open access	Opt. policy	Open access	Opt. policy	Open access	Opt. policy	Open access	Opt. policy
1	[1900;2000]	42.37	0.00	0.00	0.00	0.00	4.00	4.00	0.00	0.00
2	[1800;1900]	42.37	0.00	0.00	0.00	0.00	4.00	4.00	0.00	0.00
3	[1700;1800]	42.37	0.02	0.00	4.78	0.00	3.81	4.00	0.06	0.00
4	[1600;1700]	42.37	0.10	0.00	21.99	0.00	3.12	4.00	0.31	0.00
5	[1500;1600]	42.37	0.17	0.00	35.96	0.00	2.56	4.00	0.44	0.00
6	[1400;1500]	42.37	0.29	0.00	47.10	0.00	2.12	4.00	0.61	0.00
7	[1300;1400]	42.37	0.47	0.00	55.69	0.00	1.77	4.00	0.84	0.00
8	[1200;1300]	42.37	0.76	0.00	61.97	0.00	1.52	4.00	1.16	0.00
9	[1100;1200]	42.37	1.20	0.03	66.07	1.62	1.36	3.94	1.63	0.10
10	[1000;1100]	41.44	1.86	0.11	68.10	5.73	1.28	3.77	2.37	0.43
11	[900;1000]	38.81	3.16	0.28	68.10	10.12	1.28	3.60	4.03	1.02
12	[800;900]	35.12	5.71	0.70	66.07	13.73	1.36	3.45	7.75	2.41
13	[700;800]	30.61	12.64	2.00	61.97	16.18	1.52	3.35	19.23	6.72
14	[600;700]	25.26	33.74	7.07	55.69	17.57	1.77	3.30	59.79	23.30
15	[500;600]	19.04	143.98	39.85	47.10	17.92	2.12	3.28	304.69	130.85
16	[400;500]	11.78	211.24	107.18	35.96	17.53	2.56	3.30	541.13	353.56
17	[300;400]	5.68	567.95	355.18	21.99	12.80	3.12	3.49	1772.34	1238.79
18	[200;300]	0.97	729.42	595.87	4.78	3.15	3.81	3.87	2778.14	2308.43

Table 3.2: Open access and optimal outcomes

	Launch rate (sat./y.)	Mean collision probability (%)	Mean operational lifetime (y.)	Fleet (sat.)	Net revenue (\$m/y.)
Open Access	1713	19.80	3.21	5495	0
Optimum	1108	8.29	3.67	4066	4896

Table 3.3: Open access and optimal outcomes - Aggregate results

Table 3.2 presents the layered results. It first displays the optimal launch tax calculated for every layers. It decreases from a value of 42.37 \$m per satellite in the highest layer to 0.97 \$m to the lowest one. Remember that fragments debris created in a layer will decay and go through every lower ones, thus endangering their satellites. The external cost is thus higher in the highest layers. The high launch tax for layers that are anyway not used on the open access scenario reflects this potential external cost. Regarding the launch rates, the optimal policy always leads to fewer launches than the open access management within our specification. The first eight layers are left unused, while only the first two ones would not be profitable under open access in the long run. These lower launch rates induce smaller collision

rates, thus extending the expected operational lifespan of satellites. Using our calibration, the fleet of operational satellites in the long run is always smaller with the optimal policy than their counterparts under open access.¹²

Table 3.3 presents the aggregate results. Under open access, satellite operators launch $q^* = 1713$ satellites per year. The operational lifetime of a satellite in a clean orbital environment would be of 4 years. Due to a probability of collision¹³ of $\mu_i^*/(\lambda + \mu_i^*) = 19.80\%$, their operational lifetime drops to $1/(\lambda + \mu^*) = 3.21$ years. The steady state fleet size is $S^* = 5495$ satellites. In the optimal policy scenario, the satellite operators launch $q^o = 1108$ satellites per year. The probability for a satellite to be destroyed before its failure is $\mu^o = 8.29\%$, so its operational lifetime is reduced to $1/(\lambda + \mu^o) = 3.67$ years. The steady state size of the fleet is $S^o = 4066$ satellites.

A differentiated launch tax would be necessary to correctly incentivize satellite operators. Using aggregate data, we calculate that satellite operators would actually pay a mean tax of $l^o = 4.42$ \$million/sat. for a satellite launched in low Earth orbit. It results in a total rent of 4895 \$million/year paid to the regulator. In the perfect competition case explored here, it is exactly equal to the net revenue of the space sector.

We finally propose a sensitivity analysis based on the varying p between 15 and 27 (\$m/yr.). By doing so, we model an increase (or a decrease) in the return on investment time. Our results are presented in Figures 3.2A and 3.2B. Fleet sizes per altitude are displayed in logarithmic scale. Figure 3.2A represents the optimal fleet sizes. Figure 3.2B represents the equilibrium open access fleet sizes.

Under both the open access situation and the optimal one, fleet sizes at each altitude grow with the revenue of a satellite unit. An increased (or decreased) satellite revenue might induce a difference in fleet sizes in a given layer of several orders of magnitude. This finding strengthens the need for better economic data regarding to the satellite industry as a basis to provide more relevant policy recommendations in the future. As the satellite revenue increases, some of the highest and lowest layer that were left empty start to be used, as discussed earlier.

In addition, layer 16, going from an altitude of 400 km to 500 km, illustrates another case previously discussed.

First, focus on figure 3.2B, depicting the open access situation.

For a low enough satellite revenue (i.e., $p \leq 15$ \$million/year), this layer is left unused. As the above layers produce too much debris fragments falling into this one, it is unprofitable

¹²The first two layers represent a special case, since it is never profitable to operate satellites there under these settings.

¹³The “Collision probability (%)” column refers to the probability (here expressed in %) for an active satellite to suffer a collision during its operational life. This probability has been calculated in the paper of Guyot and Rouillon (2023) and is equal to $P_i \equiv \mu_i/(\lambda + \mu_i)$.

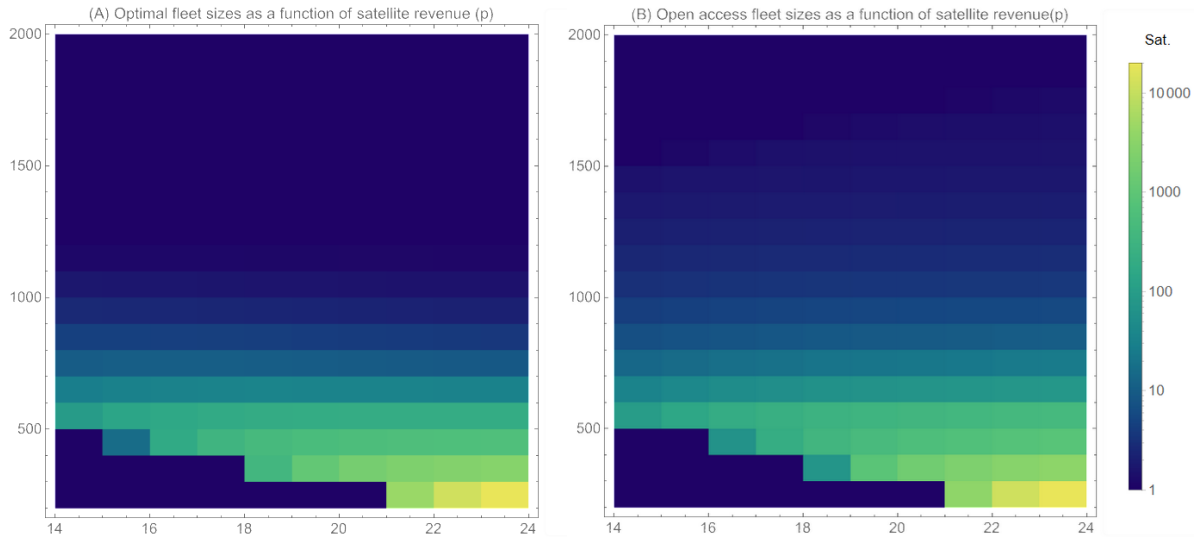


Figure 3.2: Fleet sizes per layer as a function of satellite revenue

to use it.

Now, focus on figure 3.2A that depicts the optimal situation, for a satellite revenue of $p = 15$ \$million/year. It appears that the optimal management of the orbit consists to lower the launch rate in the upper layers. By reducing the externality coming from above, this allows satellite operators to use this layer.

This illustrates the inefficiency of open access. In this extreme case, a layer that should be used is not, because of an overuse of higher altitudes in the long run.

3.7 Conclusion

In this paper, we propose a new physico-economic multi-layered model. In our model, Low Earth Orbit can be divided in N layers of altitudes where debris can go from one to another by falling back. Assuming a constant launch rate, we are able to formally analyse the equilibrium behaviours of satellite operators in both open access and the optimal allocation. We show that these exchanges of space debris imply that an optimal launch tax should differ with the aimed altitude. Using our model, we provide a numerical illustration based on a realistic calibration.

Given the current unlikelihood of a binding treaty being spontaneously joined by all major space powers, we believe that future research on the benefits of cooperation through orbital regulation on both the short and medium term will be key to guide future space policies.

3.8 Appendix

Appendix A1. Long-run equilibrium

Let us consider constant satellite planned lifetimes, rates of satellite launches and removal efforts forever, i.e., $q_i(t) = q_i$ for all t and i . We wish to analyse the steady states of the dynamical system, i.e., $x_i(t) = x_i^*$, $y_i(t) = y_i^*$ and $z_i(t) = z_i^*$ for every layer i such that:

$$\dot{x}_i(t) = \underline{\alpha}q_i + \beta_{i-1}x_{i-1}^* - \beta_i x_i^* + \eta\theta_i x_i^* (y_i^* + z_i^*) = 0,$$

$$\dot{y}_i(t) = \bar{\alpha}q_i + \lambda z_i^* - \theta_i x_i^* y_i^* = 0,$$

$$\dot{z}_i(t) = q_i - (\lambda + \theta_i x_i^*) z_i^* = 0.$$

This system can be explicitly solved as follows.

The last equation directly implies that

$$z_i^* = \frac{q_i}{\lambda + \theta_i x_i^*}.$$

Using this result, the second equation can be expressed such that

$$y_i^* = \frac{(1 + \bar{\alpha})q_i}{\theta_i x_i^*} - z_i^*.$$

Using our system of differential equations, one can also write the following expression:

$$\dot{x}_i(t) + \eta(\dot{y}_i(t) + \dot{z}_i(t)) = (\underline{\alpha} + \eta\bar{\alpha} + \eta)q_i + \beta_{i-1}x_{i-1}^* - \beta_i x_i^* = 0.$$

Using this last equation, the long run debris fragments stock thus writes

$$x_i^* = \frac{1}{\beta_i} ((\underline{\alpha} + \eta\bar{\alpha} + \eta)q_i + \beta_{i-1}x_{i-1}^*).$$

Appendix A2. Calibration of the physical model

Table 3.4 compares our calibration of the physical characteristics of a satellite with Farinella and Cordelli (1991), Lafleur (2011), Percy (2015) and Guyot & Rouillon (2023).

Coefficient	Farinella & Cordelli (1991)	Laffleur (2011)	Percy (2015)	Guyot & Rouillon (2023)	This paper	Units
α	70	70	38.06	/	/	frag./sat.
$\bar{\alpha}$	/	/	/	0.2	0.2	r.b./sat.
η	10,000	10,000	169.5	5,000	10,000	frag./sat.
$1/\lambda$	/	/	10 or 20	4.65	4	year

Table 3.4: Physical characteristics of a satellite

Table 3.5 compares our calibration of the physical characteristics of 18 low Earth orbit layers with Percy (2015). The values of our parameters β_i and $\bar{\beta}_i$ are the same than calculated by Percy (2015) and are thus marked with the = symbol. Because of the heterogeneity of actual satellites masses and volumes between layers, the values of parameters θ_i and $\bar{\theta}_i$ calculated by Percy are not strictly decreasing with altitude.¹⁴ In order to have values more in line with our use of representative satellites that are identical between layers, we used a regression over the data of Percy to obtain a strictly decreasing pattern.

Appendix A3. Stability of the steady state equilibrium

We use both the open access equilibrium (q_i^*) and the optimal policy (q_i^o) launch rates and their respective long-run orbital states (x_i^*, y_i^*, z_i^* and x_i^o, y_i^o, z_i^o) as the launch policies and new starting points of a Monte-Carlo analysis. From now on, we will illustrate our method with the open access equilibrium.

We proceed to generate 1000 new initial states for our multilayer system, by applying a random shock $\Lambda_{u,i} \in [-0.1; 0.1]$ to every orbital state variable ($u = \{x, y, z\}$), i.e.

$$\begin{cases} x_i(t=0) = (1 + \Lambda_{x,i}) x_i^* \\ y_i(t=0) = (1 + \Lambda_{y,i}) y_i^* \\ z_i(t=0) = (1 + \Lambda_{z,i}) z_i^* \end{cases} .$$

In other words, for each layer and for each orbital state variable, we simulate a random exogenous shock going from -10% to 10% . These random shocks are independent between every layers and orbital variables. We name $\underline{\Delta}_{u,i}^* = 100 * \Lambda_{u,i}$ the initial deviations in percent resulting from the exogenous shock.

¹⁴As the altitude increases, the volume of a given layer of a constant depth increases. As such, the risk of collision induced by the presence of a single object should decrease.

Layer index i	Layer's altitude range (km)	$1/\beta_i$ year		θ_i 10^{-8} /year/sat.	
		Percy (2015)	This paper	Percy (2015)	This paper
1	[1900;2000]	15052.78	=	0.66	0.63
2	[1800;1900[	11675.90	=	0.65	0.67
3	[1700;1800[	9013.06	=	0.80	0.70
4	[1600;1700[	6855.06	=	0.67	0.74
5	[1500;1600[	5215.52	=	0.95	0.78
6	[1400;1500[	3920.57	=	0.35	0.83
7	[1300;1400[	2876.50	=	0.59	0.87
8	[1200;1300[	2039.83	=	1.72	0.92
9	[1100;1200[	1390.91	=	1.05	0.97
10	[1000;1100[	893.79	=	0.71	1.02
11	[900;1000[	514.52	=	0.90	1.07
12	[800;900[	260.29	=	1.47	1.13
13	[700;800[	107.74	=	0.99	1.19
14	[600;700[	34.67	=	0.90	1.26
15	[500;600[	6.88	=	1.94	1.32
16	[400;500[	2.03	=	1.54	1.39
17	[300;400[	0.41	=	0.84	1.46
18	[200;300[	0.04	=	1.76	1.53

Table 3.5: Physical characteristics of low Earth orbit layers

We then run 1000 simulations using these new initial orbital states, for 100000 years.¹⁵ We then proceed to calculate the new deviations. For each of the 1000 simulations and for every layer, we look for the maximal absolute deviation of our variable of interest in percent, the satellite fleet size: $|\Delta_z^*| = \left| 100 * \left(\frac{z_i(t=100000) - z_i^*}{z_i^*} \right) \right|$. This value can then be compared to the maximal amplitude of the exogenous shocks applied to the system, that goes from -10% to $+10\%$.

We then apply the same method for the optimal equilibrium in order to calculate the final deviation $|\overline{\Delta}_z^o|$ in percent.

Using the open access equilibrium, we find that the maximal deviation still observed after 100000 years is $|\overline{\Delta}_z^*| = 2,20 * 10^{-4}\%$. The result for the optimal equilibrium is $|\overline{\Delta}_z^o| = 3 * 10^{-6}\%$. These results strongly suggest the stability of both our fleet sizes equilibria.

¹⁵The reason for such a long time is that decay can take tens of thousands of years. Thus, the time for the system to stabilize can amount to this order of magnitude for the highest shells.

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Chapter 4

Oligopoly competition between satellite constellations will reduce economic welfare from orbit use

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Abstract

Orbital space enables many essential services, such as weather forecasting, global communication, navigation, Earth observation for environmental and agricultural management, and national security applications. Orbit use is increasingly defined by firms launching coordinated fleets —“constellations”— of satellites into low-Earth orbit. These firms operate in markets with few or no competitors, such as the market for broadband internet provision to rural areas. How will oligopolistic competition shape the allocation of orbital space? We analyze orbital-use patterns and economic welfare when two profit-maximizing firms operate satellite constellations with sophisticated collision avoidance systems. We compare this duopoly equilibrium to public utility constellations designed and regulated to maximize economic welfare from orbit use. We show that imperfect competition reduces economic welfare from orbit use by up to 12%—\$1.1 billion USD—per year and distorts the allocation of orbital space. The nature of the distortion depends on the magnitude of constellation-related environmental damages. When damages are low, economic welfare is maximized by larger-than-equilibrium constellations. When damages are high, economic welfare is maximized by smaller-than-equilibrium constellations. Between the growing commercial and national interests in outer space and the importance of low-Earth orbit to space exploration, orbit-use management is likely to be a fruitful and policy-relevant area for economic research. We conclude with a discussion of future research directions in orbit-use management relevant to policymakers around the world.

Keywords: Space economics, game theory, satellites, oligopoly, common-pool resources.

4.1 Introduction

The number of satellites orbiting the earth has grown exponentially in the past decade—nearly half of all objects humanity had launched to space by 2021 were launched between 2011-2021 (Massey, Lucatello and Benvenuti, 2020, USSPACECOM, 2022). Of these recent objects, more than half are part of a coordinated fleet belonging to a single commercial entity (UCS, 2022, USSPACECOM, 2022). More such commercial low-Earth orbit (LEO) “megaconstellations”—constellations with hundreds or thousands of satellites—are planned or in development, with tens of thousands of new commercial satellites projected to be in orbit in the next decade. The majority of these systems are intended to provide global telecommunications services to populations that are not well-served by terrestrial telecommunications providers.

The environmental consequences of the rapid expansion of the space industry are an active area of research across multiple fields, including astronomy, aerospace engineering, economics, environmental science, law, and policy studies. There are broadly three areas of focus. Astronomy and environmental science studies have evaluated the effects of increased and more-commercialized orbit use on astronomy, dark skies, and cultural heritage (Allen, Wickham-Eade and Trichas, 2020, Massey, Lucatello and Benvenuti, 2020, Venkatesan et al., 2020). Studies in environmental science and aerospace engineering have explored the capacity of orbital space for satellites and constellation architectures, along with the effects of continued orbit use on space debris growth, collision risk, and risks to humans from falling objects (Arnas et al., 2021, D’Ambrosio et al., 2022, Lifson et al., 2022, Lewis, 2020). They also investigate interactions between rocket launches, falling debris, and Earth’s atmosphere (Boley and Byers, 2021, Byers et al., 2022), Radtke, Keschull and Stoll, 2017, Ryan et al., 2022). Law, policy, and economics studies have focused on the legal mechanisms available to address risks on orbit and to people on Earth, the role of economic incentives in space debris creation and collision risk growth, and on developing and quantifying the benefits of policy mechanisms to address space debris and collision risk (Adilov, Alexander and Cunningham, 2015, Adilov, Alexander and Cunningham, 2022, Gilbert and Vidaurri, 2020, Grzelka and Wagner, 2019, Lifson and Linares, 2021, Macauley, 2015, Muñoz-Patchen, 2018, Rao, Burgess and Kaffine, 2020, Rouillon, 2020, Weeden, 2011).

Much less attention has been devoted to the economic consequences for consumers of orbital-use concentration among a few large operators. Yet orbital space is increasingly dominated by a handful of commercial operators who face limited competition. Fig. 4.1 illustrates this situation: Panel A shows the recent growth in fleet sizes, Panel B highlights regions of orbital space where a few operators own many satellites, and Panels C and D show orbital space has gone from being dominated by government-operated satellites to commercially-operated satellites. Concentrated use of orbital space may raise issues distinct from “open-access”

use, where many small operators ignore their effects on each other. While economic theory and empirical evidence show market concentration can lead to higher prices, lower product quality, and delayed innovation (Busso and Galiani, 2019, Daughety and Reinganum, 2008, Stiglitz and Dasgupta, 1982), it may also improve environmental quality relative to open-access resource use (Adler, 2004, Cropper and Oates, 1992, Herrera, Moeller and Neubert, 2016, Levhari and Mirman, 1980). How will competition among a small number of constellation operators impact orbital space allocations and service quality? How large are the gains from optimal constellation regulation, and how do they vary with the magnitude of environmental externalities? The growing role of commercial motives in the expansion of the space sector has highlighted a need for coupled-systems frameworks that link physical and economic models of orbit use to answer these questions (Weinzierl, 2018).

To address these knowledge gaps, we build a tractable coupled physico-economic model combining microeconomically-grounded operator behavior and heterogeneous consumer demand with rich physical structure. We use this model to quantify the economic welfare loss and distortion in orbital allocations from duopoly constellation operators competing for orbital space and market share relative to public utility constellation systems optimally regulated to maximize global public welfare. These public utility systems use orbital space in the public interest, balancing the benefits of better telecommunications service against the costs of externalities like orbital congestion and environmental damages on Earth.

This is a classic problem of regulating an oligopolistic sector with environmental externalities (Barnett, 1980, Cropper and Oates, 1992, Karp, 1992, Katsoulacos and Xepapadeas, 1995). While it is challenging to address multiple interacting market failures, we find that public utility constellations can increase annual economic welfare from LEO satellite constellations by up to 12%.

Our model is built from a combination of physical and economic first principles as well as reduced-form models that have been validated in other settings (Lifson et al., 2022, Wauthy, 1996). We calibrate the model using publicly available data on telecommunications service offered by Starlink and announced by OneWeb (Butash and Rusch, 2022, Ookla, 2022, UCS, 2022), as well as economic research on individuals' willingness-to-pay (WTP) for different features of telecommunications service. We assume that constellations utilize "slotting" architectures to avoid collisions with other orbiting objects but that those avoidance maneuvers disrupt service (Arnas et al., 2021, Lifson et al., 2022). Our model assumes that megaconstellation operators deploy their systems sequentially and set service prices to maximize their own profits. Economic welfare, or "total surplus", is measured as the annual sum of economic benefits received by consumers given their WTP for satellite telecommunications service and service prices (i.e. "consumer surplus") and the profits earned by operators (i.e. "producer surplus"). For example, a total surplus of \$10 billion per year means that the difference between the maximum amount consumers were willing to pay and the cost of producing the

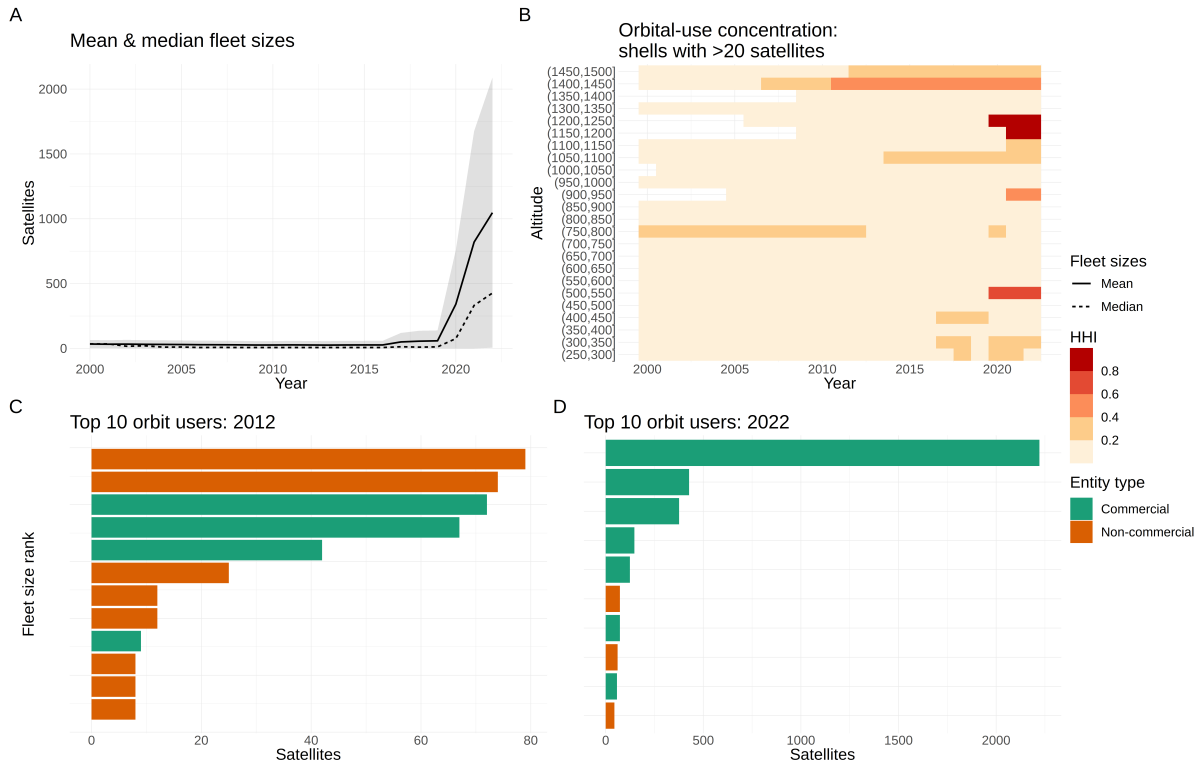


Figure 4.1: State of orbit use over 2000-2022. (A) Growth of average (dotted) and median (solid) satellite fleet sizes across operators (active satellites only). Shaded areas show the average fleet size ± 1 standard deviation. (B) Herfindahl-Hirschman Index (HHI) for active satellite ownership in 50-km orbital shells. HHI is a standard economic measure of concentration used in competitive and antitrust analysis, computed as the squared share of objects in a shell owned by a single entity (US Department of Justice, 2018). Higher numbers indicate a larger share is owned by a smaller number of actors. Shells with fewer than 20 satellites (10th percentile) are truncated to zero for visualization. (C) Top ten operators by active satellite count in 2012. “Non-commercial” entities include civil government, military, and amateur operators. (D) Top ten operators by active satellite count in 2022. Data compiled from (UCS, 2022, USSPACECOM, 2022).

service was \$10 billion.

Though our model is deliberately simplified for tractability and our results are order-of-magnitude estimates, the framework we develop is general and our findings are applicable to existing and planned megaconstellations. Our model lays the foundations for more detailed models of orbit use by megaconstellations. Our results yield new insights into how the concentration of orbital space among a small number of commercial players may affect economic and environmental outcomes, and supports evidence-based policymaking to promote the sustainable development of the space sector.

4.2 Model

Orbital space allocations are represented by the altitude of the constellation (location)

and the number of satellites deployed there (size). Under duopoly use of orbital space, two firms—a first mover (“leader”) and a second mover (“follower”)—provide telecommunications services to consumers on Earth. We consider only two firms for tractability and to represent the near-term situation in orbit. The demand for satellite telecommunications services from each firm is driven by consumer preferences for service quality, which is defined as an index of service availability (more is better), latency (less is better) and bandwidth (more is better). Availability is limited by terrestrial coverage and orbital congestion: the less area the constellation covers at any instant or the more time it spends maneuvering to avoid collisions, the less available it is for consumers. We describe the key model components here and provide details on assumptions, functional forms, and calibration in the SI Appendix.

Quality, availability, latency, and bandwidth. Consumers evaluate telecommunications services based on availability, latency, and bandwidth, which together determine overall service quality. Availability, influenced by coverage area and satellite maneuvers, refers to the fraction of time a service is accessible, with higher availability being more desirable. Coverage area depends on factors such as satellite altitude and beam angle—all else equal, higher altitudes offer greater coverage—while satellite maneuvers are necessary to avoid collisions. Latency is the average time for a signal to travel between the consumer and the satellite, with lower latency preferred. Bandwidth represents the data transmission rate or throughput, with higher bandwidth desired for faster data transfer. Bandwidth is approximately proportional to the ratio of satellites to consumers.

Location, size, and congestion. We discretize orbital space into a series of non-overlapping spherical shells. Operators choose a single shell in which to place their constellation. A constellation’s location and size in orbit determines the characteristics of its telecommunications service (i.e. availability, latency, and bandwidth). Lower altitudes allow lower latency but require more satellites to provide full coverage. Larger sizes enable more bandwidth and coverage, but increase the number of maneuvers required to avoid collisions and thus reduce availability. We refer to these maneuvers as “orbital congestion”. Lower orbital shells have smaller volumes; all else equal, a constellation at lower altitudes will face greater congestion than it would at higher altitudes. The fundamental tradeoffs faced by satellite constellation operators involve choosing system location and size to optimize service quality. If a system is set too high or is too large, the rise in latency or collision avoidance maneuvers may offset improvements in coverage or bandwidth. On the other hand, a system that is too low or too small may suffer from the reverse.

Following prior works, we use kinetic gas theory to predict close approaches between satellites within an orbital shell (Lifson et al., 2022) (SI Appendix). A maneuver is conducted when satellites approach within a specified safety margin of each other. All else equal, higher maneuver safety margins lead to more maneuvers and greater reductions in availability. The maneuver safety margin reflects a combination of technical, behavioral and regulatory factors,

such as constellation slotting architectures (D’Ambrosio et al., 2022), positional uncertainty in object trajectories (Arnas et al. (2021)), the operators’ risk tolerance, and implementation of avoidance guidelines (IADC, 2017). We assume all objects use a common safety margin and calibrate it to match open-source analysis of Starlink maneuvers (Lewis, 2022). We assume only one satellite involved in a close approach within the safety margin maneuvers, each taking turns.

Satellites. Satellites are costly to produce and place in orbit. The cost of a satellite in orbit reflects the cost of materials, energy, and infrastructure required to launch it, maintain the desired altitude, and provide service. The interaction between atmospheric drag—stronger at lower altitudes—and lift energy—more required for higher altitudes—make the cost of a satellite first decline and then increase with altitude (De Pater and Lissauer, 2015). The satellite cost function is calibrated to reflect prior literature and public statements regarding Starlink satellites (Osoro and Oughton, 2021, Wang, 2019). The coverage and bandwidth per satellite at a given altitude are derived from physical first principles and calibrated based on prior literature and analysis of Starlink and OneWeb satellites (Ookla, 2022, Osoro and Oughton, 2021). (SI Appendix).

Competition. Firms deploy constellations knowing that their location and size choices are irreversible, but that their service prices can be adjusted continuously. The irreversibility of location and size choices reflects the high cost of redesigning and re-licensing a constellation to operate in a different configuration once it is fully deployed (Prescott and Visscher, 1977, Robson, 1990). Firms therefore compete in two stages: first in a sequential-move location-and-size-choice game, and second in a simultaneous-move price-setting game. The leader anticipates the follower’s entry and chooses their location and size to maximize their own profits, while the follower chooses their location and size to maximize their own profits given the leader’s choices. The leader thus alters the follower’s location and size choice to their own advantage. Firms are forward-looking and anticipate the outcomes of the pricing subgame when choosing locations and sizes.

Consumers. Consumers choose the service that provides them with the most satisfaction given service characteristics and prices (i.e. maximizes their utility). Consumers are heterogeneous and value service quality differently. We calibrate their preferences to reflect recent consumer survey results (Liu, Prince and Wallsten, 2018)). We focus on end consumers rather than intermediaries. The market share captured by each firm is determined by the consumer who is indifferent between service offerings. Consumers who place a higher value on service quality choose the firm with higher service quality. All else equal, the more consumers a system serves, the less bandwidth is available to all consumers (i.e. there are network congestion effects). To reflect a near-term scenario with two operational constellations, in the benchmark case we consider a market with 10 million consumers globally.

Scenarios. We consider three scenarios: the duopoly equilibrium, in which firms choose

locations, sizes, and prices to maximize their profits and consumers choose a service to maximize their utility; and two types of public utility systems, with one or two constellations. We use the term “public utility system” to refer to a system of constellations, in a given scenario, which are designed and regulated to maximize global economic welfare. A one-constellation public utility system shows the potential gains from regulation while providing equitable access to all consumers, while a two-constellation public utility system shows the potential gains from regulation while providing differentiated service to consumers. The optimal public utility system is the one which provides greater economic welfare. We use a public utility framework to consider optimal use of orbital space since, due to high fixed costs, perfect competition in this market is unlikely. We use these scenarios to quantify the maximum benefits of regulating orbit use relative to the status quo. In all scenarios, we include the background traffic of objects (excluding Starlink and OneWeb) recorded by Space-Track.org as of December 26, 2022 (USSPACECOM, 2022). We assume there are no environmental damages on Earth from satellite constellations in the benchmark calibrations, and conduct sensitivity analysis over the magnitude of these damages to identify key thresholds. The public utility systems internalize the environmental costs of constellations when designing the systems.

4.3 Results

Table 4.1 shows the constellation design parameters under each scenario in the benchmark calibration with no environmental damages (SI Appendix). In the duopoly equilibrium, the leader anticipates the follower’s entry and launches a larger constellation at a lower altitude (29750 satellites at 500 km), forcing the follower to choose a smaller constellation at a higher altitude (1945 satellites at 603 km). These design choices give the leader higher availability and bandwidth and lower latency than the follower, enabling the leader to capture the majority of the market—particularly the most lucrative segment. Both the duopoly leader and the one-constellation public utility system are placed near the cost-minimizing altitude of 500 km (see SI appendix). By moving first, the duopoly leader is able to claim the better location. The spacing in the duopoly case reflects the logic of competition in vertically-differentiated markets: increasing the differentiation between the service offerings increases both firms’ profits, as it decreases the “toughness” of competition between the two for indifferent consumers (see SI appendix).

In the two-constellation public utility system, constellations are placed at lower altitudes (480 and 515 km) and differently sized compared to the duopoly system—the larger system is smaller than the duopoly leader’s (26365 satellites), while the smaller system is larger than the duopoly follower’s (18199 satellites). The one-constellation public utility system is the largest of all (45151 satellites) and placed slightly lower than the duopoly leader’s (495 km). The two public utility constellations are located around the cost-minimizing orbital altitude

Scenario	Duopoly		Two public utility constellations		One public utility constellation
	Leader	Follower	Larger	Smaller	
Mean altitude [km]	500	603	480	515	495
Size [sats]	29750	1945	26365	18199	45151
Latency [ms]	33	34	33	33	33
Bandwidth [Mb/s]	90	43	122	97	111
Availability [%]	100	69	100	100	100
Market share [%]	83	17	53	47	100

Table 4.1: Comparisons of constellation designs under different scenarios in the benchmark calibration. All values are rounded to the nearest integer.

(500 km) with just enough separation distance to avoid between-constellation congestion. As both one- and two-constellation public utility systems use similar altitudes, the marginal cost of an additional satellite under both systems is comparable, leading to similar total system sizes. Despite having fewer satellites, market segmentation and reduced network congestion allow the larger constellation in the two-constellation system to offer higher bandwidth to consumers who value service quality more. While this benefits the larger constellation’s users, it comes at the expense of lower bandwidth for users of the smaller constellation, who value service quality less. Both public utility systems deliver availability and latency comparable to the duopoly leader’s.

Figure 4.2 shows the aggregate annual global economic welfare (panel A) and orbital congestion (panel B) created by each system type in the benchmark calibration. Welfare is computed as the global annual total surplus generated by the system as a whole. Orbital congestion (i.e. collision avoidance maneuvers within and between constellations) is computed as the expected daily number of maneuvers for each system (SI Appendix). We project that shifting from duopoly constellations to a one-constellation public utility system would increase annual economic welfare by around \$1 billion USD (roughly 10%), while a two-constellation public utility system would increase annual global economic welfare by around \$1.1 billion USD (roughly 12%). Though the larger public utility constellation sizes and lower locations increase welfare, they also increase orbital congestion. Compared to duopoly constellations, we project that a one-constellation public utility system would induce around 5,291 additional collision avoidance maneuvers per day (roughly a 126% increase), while a two-constellation public utility system only induces around 703 additional maneuvers per day (roughly a 17% increase). These maneuvers are conducted to avoid collisions between satellites in the same constellation—both in equilibrium and under public utility designs the constellations are placed far enough apart that no maneuvers are necessary to avoid collisions between satellites from different constellations. In the case of the two-constellation public utility system, the spacing is just sufficient given the discretization of orbital space to avoid between-constellation congestion (SI Appendix).

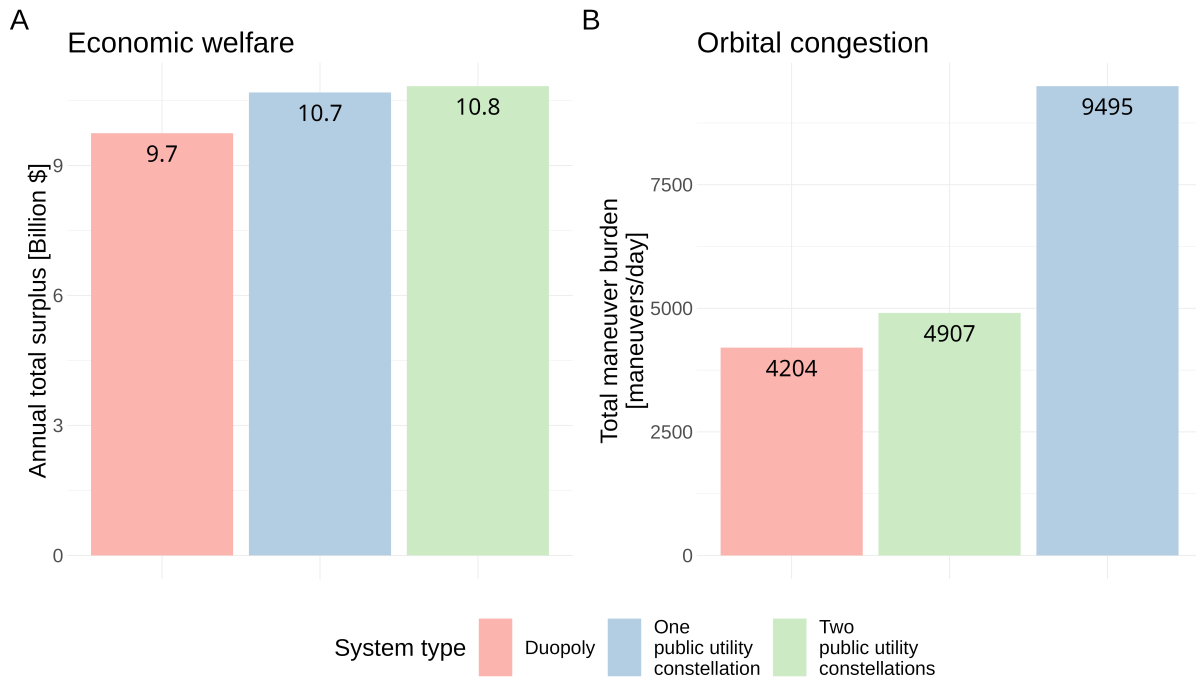


Figure 4.2: Equilibrium and public utility constellation economic welfare and congestion under benchmark calibration. (A) Annual economic welfare generated by each system type. (B) Daily expected congestion for constellations under each scenario.

Figure 4.3 shows how the sizes and locations of public utility constellations change as the number of consumers served (panels A and C) and maneuver safety margin (panels B and D) increase. At very low market sizes, a single public utility constellation can serve the market most efficiently, and the one- and two-constellation systems are identical (panels A and C). As the market grows, larger constellations are needed to provide sufficient service quality (panel A). Despite the increase in orbital congestion, the public utility systems only raise altitude slowly as market size increases (panel C). In the two-constellation public utility system, the constellations are separated by the minimal distance necessary to avoid between-constellation congestion (panel C). When the safety margin is low, the one-constellation public utility system can be larger (panel B) and placed at lower altitudes (panel D), providing lower latency and higher bandwidth with minimal congestion. As the safety margin increases, it becomes necessary to make it smaller to reduce orbital congestion. The two-constellation public utility system does not follow this pattern. As the safety margin increases, satellites are reallocated from the larger constellation to the smaller one (panel B), reducing overall orbital congestion with smaller impacts on service quality. Both constellations are moved lower, reducing latency and partially offsetting the effect of lower availability (panel D).

Figure 4.4 shows how the economic welfare gain from public utility systems (relative to duopoly) scales with the number of consumers served. The two-constellation public utility system is economically optimal, providing uniformly greater welfare up to 25 million con-

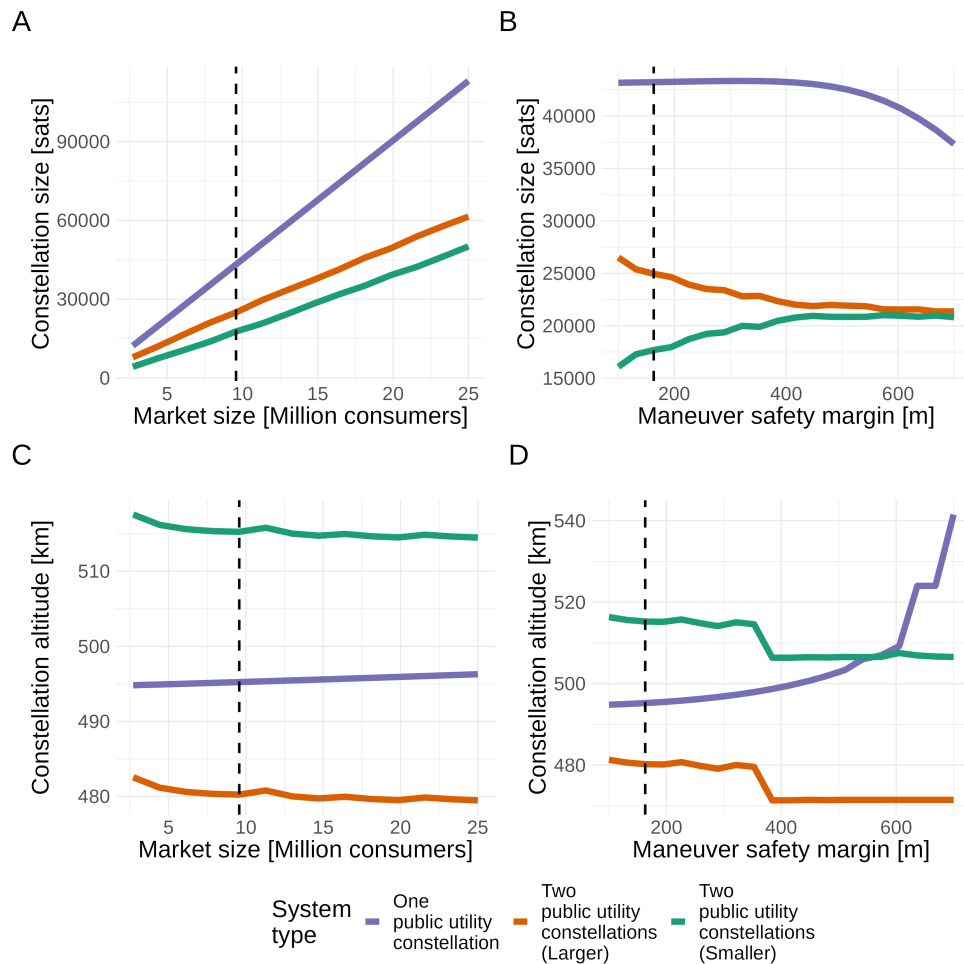


Figure 4.3: Public utility constellation sizes and locations as number of consumers served and safety margin increase. Panels A and C show how constellation size and location change with the number of consumers served. Panels B and D show how constellation size and location change with the safety margin. The dashed vertical lines show the benchmark calibration. Irregularities in the two-constellation problem’s optimization surface introduce numerical artifacts in the solution paths.

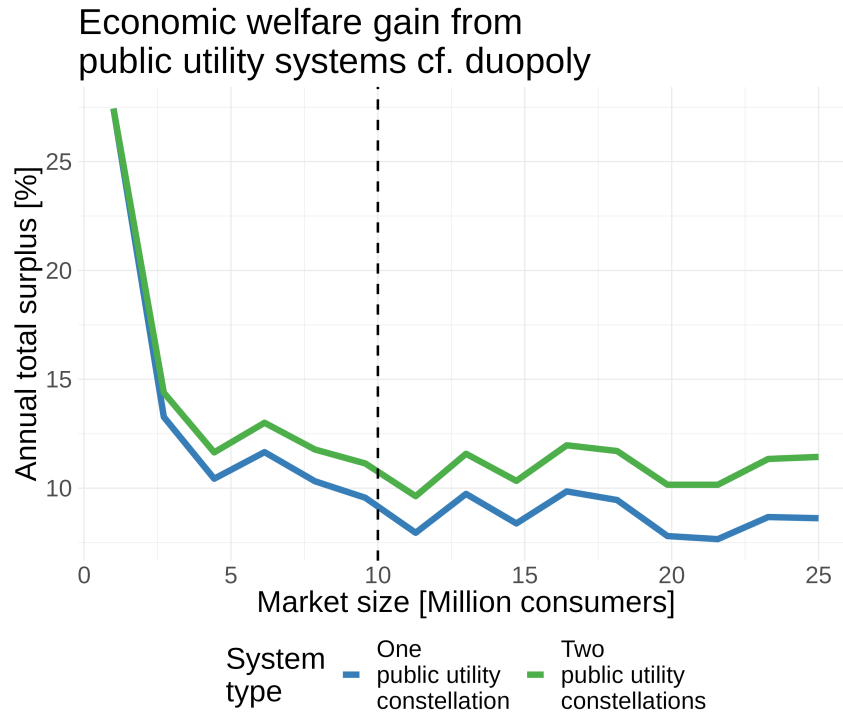


Figure 4.4: Percentage gain in economic welfare from public utility systems relative to the duopoly equilibrium. The orbital shell discretization for the duopoly problem introduces numerical artifacts. The dashed vertical line shows the benchmark calibration.

sumers served (the maximum we simulate). The percentage gain from the two-constellation system is decreasing in the number of consumers served—from around 25% at 1 million consumers to around 10% at 25 million consumers. The percentage gain from the two-constellation system decreases to a little over 10% when 25 million consumers are served globally. The percentage gain from a one-constellation system follows the trend of the two-constellation system, reaching a little over 5% with 25 million consumers. The scaling with the number of consumers served reflects the fact that total welfare is increasing in the market size under all system types including duopoly. Thus, the monetary value of a 10% gain at 20 million consumers exceeds the value of a 20% gain at 10 million consumers (SI Appendix).

Figure 4.5 explores how the gains from the economically-optimal two-constellation system scale with both market size and maneuver safety margin. Since we assume all avoidance maneuvers are successful, reduced safety margins correspond to a best-case for better avoidance technologies/practices (i.e. improvement at zero cost). These include better space situational awareness, slotting architectures, control systems, and satellite coordination. Both the percentage and absolute monetary gains are greatest at large market sizes and large safety margins.

Figure 4.6 shows the marginal welfare cost of higher safety margins, i.e. the change in economic welfare from increasing the safety margin. Higher safety margins imply greater

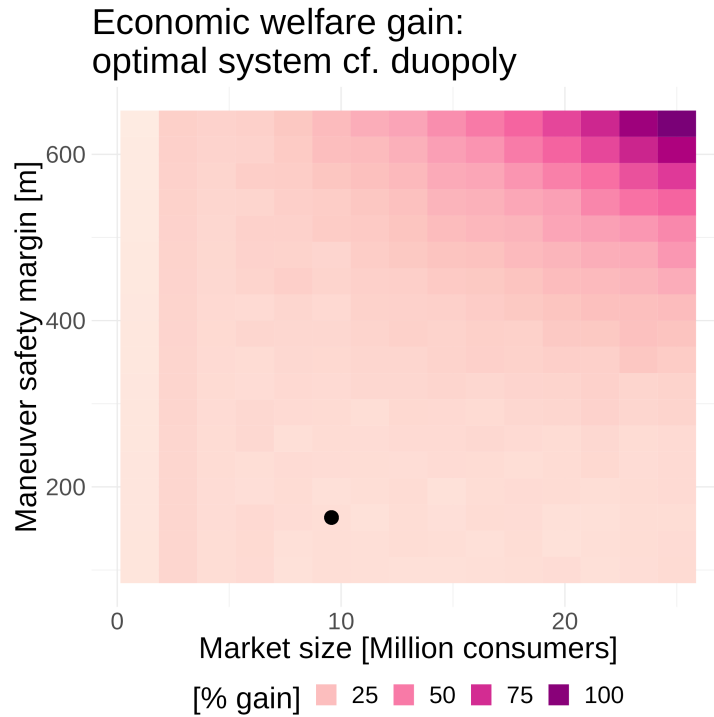


Figure 4.5: Percentage gain in economic welfare from the economically-optimal two-constellation public utility system relative to the duopoly equilibrium. The black dot shows the benchmark calibration.

orbital congestion, as the same distribution of orbiting objects require more maneuvers. The marginal welfare cost is generally increasing in the safety margin, though it is highest for the one-constellation public utility system. This is driven by the fact that the one-constellation system does not spread satellites across multiple locations. As the safety margin increases, it is forced to reduce the total number of satellites faster to manage congestion (Fig. 4.3B). The marginal welfare cost of higher safety margins is lowest under the two-constellation public utility, since it efficiently reallocates satellites across constellations to maintain service quality. The duopoly faces a marginal welfare cost between the two public utility designs, as it disperses satellites across multiple orbits but does so inefficiently.

Finally, Figure 4.7 illustrates how environmental damages affect public utility and duopoly constellation sizes (Panel A), as well as their subsequent effects on economic welfare (Panel B). These damages encapsulate the annualized value of various environmental externalities other than orbital congestion, such as rocket emissions, orbital debris, ozone layer degradation, and re-entry impacts on people and property (SI Appendix).

Panel A shows that the public utilities progressively decrease their system sizes as environmental damages increase, with total numbers of satellites matching the duopoly at approximately \$150,000 in damages. The two-constellation public utility then transitions to a single constellation and no longer provides full-market coverage. This causes the total number

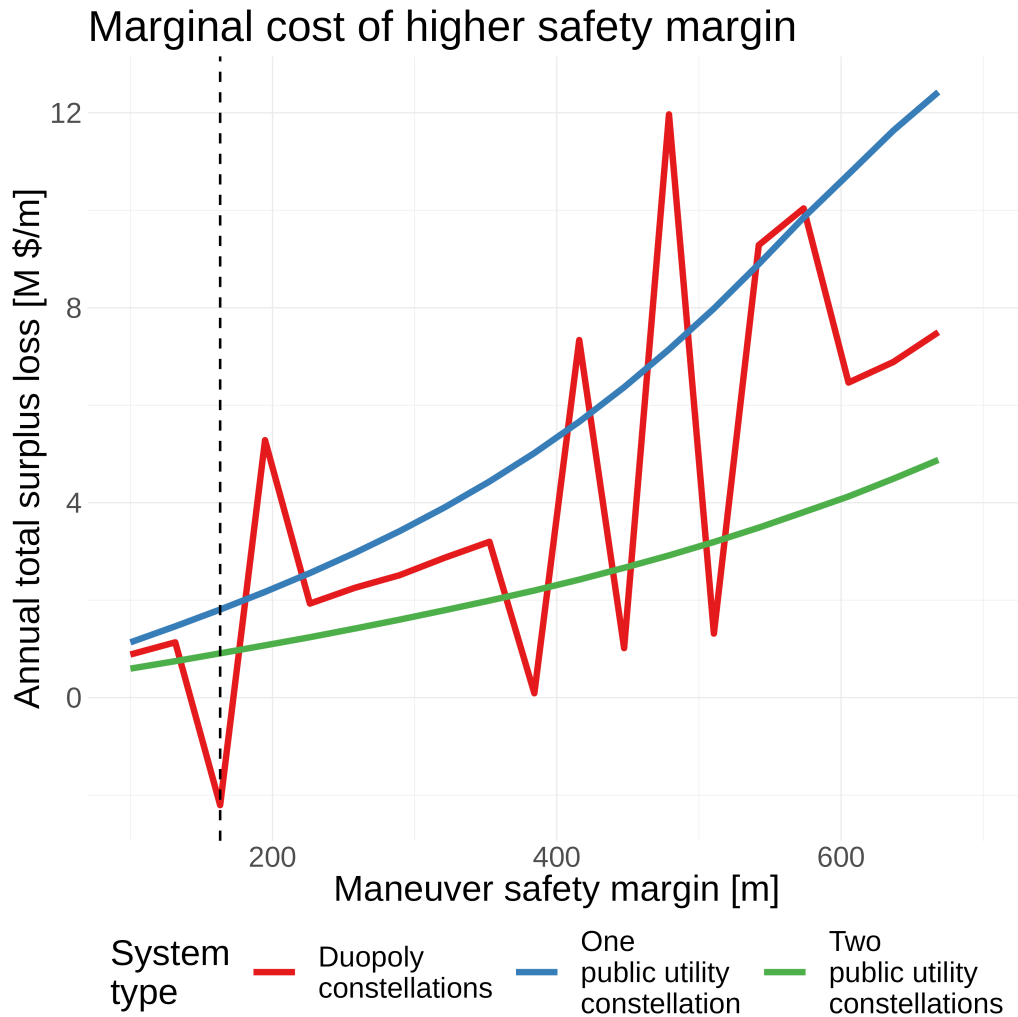


Figure 4.6: Reduction in total welfare per unit increase in maneuver safety margin. Numerical artifacts are introduced in the duopoly calculation due to orbital shell discretization. The dashed vertical line shows the benchmark calibration.

of satellites in the (formerly) two-constellation public utility to dip below that of the one-constellation public utility. The two-constellation system continues until the damages reach around \$600,000, at which point even a single satellite generates negative economic welfare. In contrast, the one-constellation public utility maintains its market-wide non-differentiated service until damages reach around \$330,000. Beyond this point, the minimal constellation necessary to provide desirable service to the whole market generates negative welfare. Since the one-constellation public utility must provide uniform service to the entire market or none at all, it ceases operations. The system altitudes change little or not at all (SI Appendix).

Panel B shows the net economic welfare generated by the economically-optimal two-constellation system and the duopoly as environmental damages increase. At around the same level of damages where the one-constellation public utility shuts down, the duopoly's use of orbital space generates net negative economic welfare. In contrast, the two-constellation public utility continues to provide positive economic welfare until it shuts down, reducing its size to avoid generating more environmental damages than surplus from telecommunications service. There is also a range of annualized damages—roughly \$100,000-\$250,000—where the duopoly provides greater welfare than the one-constellation public utility. This is due to the gains from market segmentation (even under the duopoly) relative to providing uniform service quality to all consumers.

4.4 Discussion

Space in low-Earth orbit is increasingly concentrated in the hands of a small number of competing commercial telecommunications firms. Our analysis suggests that this competition will be a critical factor determining how orbital space is allocated, and that improving economic welfare from LEO telecommunications services will require altering the allocation of orbital space. Failing to do so will limit the degree to which economies benefit from the use of low-Earth orbit.

Fundamentally, there are two interacting market failures in orbit use. The first, identified in prior literature, is the open-access problem. Lacking exclusive property rights to orbital slots, operators do not account for how their behaviors impact other orbit users (Adilov, Alexander and Cunningham, 2015, Rao, Burgess and Kaffine, 2020, Rouillon, 2020). On its own this market failure can be remedied through environmental policy, e.g. externality-correcting taxes on orbiting satellites. The second, which we address here, is oligopolistic competition between orbit users. Oligopolistic megaconstellation operators utilize orbital space to exercise market power. On its own this market failure can be remedied through competitive or antitrust policy, e.g. public utility regulation of megaconstellations. These market failures cut in opposite directions: while the open-access problem will lead to an excessive number of objects in orbit, oligopolistic competition will lead to too few satellites

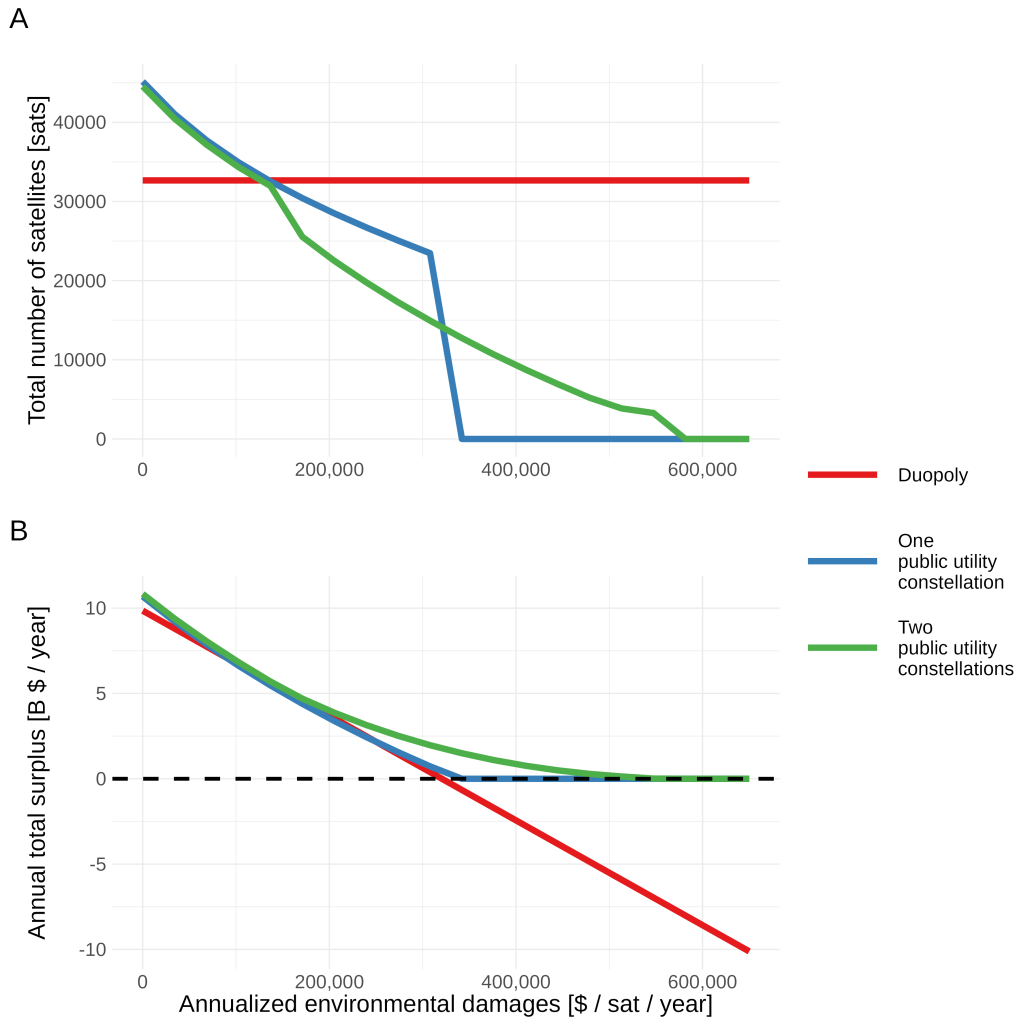


Figure 4.7: Effects of greater environmental damages on optimal constellation designs and economic welfare.

in orbit.

The large spacing and size differences between the duopoly constellations reflect the firms' incentives to increase product differentiation and reduce the toughness of price competition (Prescott and Visscher, 1977, Wauthy, 1996). The low service quality levels in the duopoly equilibrium reflect firms' incentives to minimize production costs. The combined effect of these incentives is lower service quality—a common feature of oligopolistic competition in markets for differentiated products (Prescott and Visscher, 1977, Shaked and Sutton, 1987, Sutton, 1986, Wauthy, 1996)—and lower orbital congestion. Such “excessive conservatism” is a common feature of oligopolistic use of natural resources (Adler, 2004, Herrera, Moeller and Neubert, 2016, Levhari and Mirman, 1980, Stiglitz and Dasgupta, 1980). Regulating natural resource use under multiple market failures is challenging, often requiring more-complex policies than if the market failures existed in isolation (Cropper and Oates, 1992, Barnett, 1980, Karp, 1992, Katsoulacos and Xepapadeas, 1995).

We have focused on oligopolistic competition with two constellation operators, reflecting the near-term situation with Starlink and OneWeb. Public filings suggest more firms are likely to enter the market soon, e.g. Amazon's Kuiper and Telesat's Lightspeed (Butash and Rusch, 2022). Our analysis provides a useful reference point for understanding how competition between these operators is likely to evolve. The economic literature suggests that entry into such markets may be limited (partly due to choices made by first-movers and incumbents), and that more entry is not necessarily welfare-enhancing (Anderson and Engers, 1992, Crabbé and Van Long, 1993).

Though we abstract from the fixed costs of deploying a constellation—e.g. designing the system, obtaining regulatory clearances for ground stations and spectrum licenses—to focus on competition between two firms, the fixed costs can be substantial. These fixed costs make perfect competition—with many constellation operators serving small portions of the market, none able to individually affect market outcomes—unlikely to materialize. Indeed, it is an open question whether the market can support multiple satellite constellations even if they target different market segments. History suggests that large LEO satellite constellations tend to face significant economic challenges—Iridium, an early example, went bankrupt in the early 2000s (Daehnick et al., 2020). More recently, OneWeb filed for bankruptcy in 2020 (Reuters, 2020). These considerations suggest that imperfect competition is likely an important feature to consider when studying orbit use.

Finally, we show that the environmental damages caused by satellites over their lifecycle play a critical role in determining the relationship between oligopolistic and economically-optimal orbit use. When environmental damages are low, imperfect competition causes too few satellites to be in orbit relative to the optimal public utility system. As damages increase the economically-optimal system shrinks while the duopoly fleet remains unchanged, resulting in too many satellites in orbit relative to the optimal public utility system.

Limitations and future research. Following prior work on constellation slotting architectures, we assume all collision avoidance maneuvers are successful (Lifson et al., 2022). While this assumption has been empirically validated thus far, eventually some fraction are likely to fail and generate debris fragments which induce further maneuvers. Such outcomes will likely reduce the sizes of the duopoly and public utility systems and may create a further incentive to place constellations at lower altitudes, where debris will decay and burn up in Earth’s atmosphere more rapidly. We also do not account for congestion created by the process of replenishing constellations (e.g. orbit-raising maneuvers) or the congestion created by avoiding satellites which are deorbiting. These issues will multiply as more constellations are deployed and the demand for satellite telecommunications services grows. Incorporating such issues will again likely alter the design of the economically-optimal public utility constellation system. Future research in this area should incorporate debris and collision risk dynamics into models of strategic orbit use behaviors. Finally, we assume consumers and bandwidth demands are uniformly distributed on the globe and over the day. Spatial and temporal non-uniformities, e.g. reduced service usage at night boosting peak bandwidth, may create further opportunities for market segmentation (SI Appendix).

Though we do not explicitly model debris formation and decay, the public utility constellation designs we calculate are at relatively low altitudes. Such low placement should ensure that orbital debris produced burns up in the atmosphere within 25 years, consistent with current international disposal guidelines (IADC, 2007). However, using the atmosphere to dispose of satellites comes at the cost of depositing large quantities of satellite materials in the upper atmosphere, damage to the ozone layer, and re-entry risks for people and property on Earth (Boley and Byers, 2021, Byers et al., 2022, Radtke, Kebschull and Stoll, 2017, Ryan et al., 2022). Large satellite constellations also impose costs on ground-based observation systems (Massey, Lucatello and Benvenuti, 2020, Venkatesan et al., 2020), i.e. light pollution. Though we identify an aggregate cutoff level of annualized damages such that the optimal public utility fleets are smaller than the duopoly fleet (\$150,000 per satellite per year), our model does not speak to how these damages will be distributed. Unfortunately, detailed estimates of the environmental damages and distributions of these externalities are not yet available. While best practices for Life Cycle Assessment of large satellite constellations are still developing, existing research and guidelines note that factors such as the propellant and motor used in rockets deploying the constellation can strongly affect the system’s environmental damages (Dallas et al., 2020, Maury et al., 2020). Future research should study these damages and incorporate them into more detailed physico-economic models of orbit use.

Despite these issues, satellite constellations may help spur innovations in small satellite designs, which can have positive effects for scientific and astronomical discovery (Allen, Wickham-Eade and Trichas, 2020). On the other hand, a long-standing economic literature has identified oligopolistic use of natural resources as a barrier to technological innovation

(Stiglitz and Dasgupta, 1980, Stiglitz and Dasgupta, 1982). Developing better understanding of policy designs to address interactions between multiple market failures—particularly environmental externalities, imperfect competition, and positive innovation spillovers—may prove useful for future sustainable growth policies in other settings.

We have also abstracted from issues of national strategic uses of orbital space. While satellites owned and operated by national militaries are a declining share of satellites in orbit (largely due to the growth of megaconstellations), militaries and governments also act as important customers for megaconstellation operators, and megaconstellations may serve important national strategic interests (The Economist, 2022-a). Governments facing such incentives may prefer constellation operators they purchase from to not serve other governments, or even to have their own systems, driving demand for multiple systems. Such demand is evident in discussions around a European constellation, the UK government’s interest in supporting the purchase of OneWeb following their bankruptcy in 2020 (the UK government now holds a roughly 19% stake in OneWeb (The Economist, 2022-b), and potentially in the Chinese government’s support for the GuoWang system (Council of the EU, 2022, Jones, 2022, UK Department for Business, 2020). While our findings regarding economic welfare for civilian consumers are robust to such use cases, they raise the important point that governments may be willing to trade economic welfare for other objectives when using orbital space.

Finally, we use the term “public utility system” to refer to a system of constellations (one or two, depending on the scenario) which are designed and regulated to maximize global economic welfare. While public utility-like uses of space resources have been considered for positioning, navigation, and timing services or Earth observation data, we are unaware of similar proposals for telecommunications megaconstellations (Aschbacher, 2017, NCOSBP, 2021). We abstract from regulatory issues analyzed in the economic literature, such as asymmetric or incomplete information, capital bias, regulatory capture, and management of network effects (Belleflamme and Peitz, 2018, Brennan, 2009, Cicala, 2015, Cicala, 2022, Knittel, Metaxoglou and Trindade, 2019, Laffont and Tirole, 1994). For example, SpaceX is currently one of the only firms with reusable rockets and is vertically integrated with a satellite constellation. Similarly, Amazon’s planned satellite constellation would be vertically integrated with several internet services such as entertainment, shopping, and cloud computing. Such integration may provide different incentives for innovation between the private and the public sectors. Given the unique environmental, economic, and geopolitical features of orbit use, optimal public utility regulation of satellite megaconstellations may look very different from public utility regulations in other sectors—even from terrestrial telecommunications providers. Indeed, economic theory suggests market power should be regulated on a case-by-case basis (the “rule of reason” approach) rather than through rigid “per se” rules across industries (Tirole, 2015) .

It may be possible to conduct such regulation under existing space governance institutions. In particular, Article VI of the Outer Space Treaty requires signatories to authorize and continually supervise the activities of their space industries (UNODA, 1967). This suggests the potential for nationally-administered but internationally-coordinated constellation regulatory systems. Such coordination—extending to radio spectrum allocations, space traffic management, and orbital debris mitigation and remediation—poses significant challenges, particularly given its impacts on the distribution of service access and its national strategic implications. Future research should study international satellite constellation regulatory competition and seek strategies for enhancing its outcomes.

Oligopolistic competition between orbit users will drive inefficient orbital-use patterns, with low and highly unequal service quality. These inefficiencies persist even with improvements in collision avoidance technologies and practices. Environmental externalities like rocket emissions, debris accumulation and re-entry, and light pollution worsen the inefficiency of oligopolistic orbit use. Public utility regulation of constellations could substantially improve global economic welfare from orbit use. These benefits grow as orbital space grows more congested and constellations serve larger markets. While there is much to be done to design and implement these regulations, recognizing and quantifying the tradeoffs and complementarities involved is an important step forward.

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4.5 Supporting Information

4.5.1 Model overview

We model competition between firms for orbital space and telecommunications market share as a two-stage game. Constellation operators are indexed by $i = F, L$. In the first stage, they compete in a sequential-move (Stackelberg) game to choose their constellations' altitude and size. Firm L (the Leader) deploys their constellation first and firm F (the Follower) deploys second.¹ Both players are rational, so the Follower best-responds to the Leader's choice and the Leader anticipates the Follower's best-response when designing their constellation. With their constellations deployed, in the second stage, firms play a simultaneous-move price-setting game to compete for demand from a mass of N consumers.²

Deploying a constellation means choosing a number of satellites Q_i to maintain and a mean orbital altitude h_i to place them. These design choices determine the overall service quality x_i . Service quality is a function of the constellation's global Earth coverage α_i , congestion loss β_i , latency L_i , and bandwidth S_i . Earth coverage is increasing in altitude and constellation size. Congestion loss is increasing in the constellations' sizes and proximity to each other. Latency is increasing in altitude. Bandwidth is increasing in constellation size.

The annualized unit cost of manufacturing, deploying and maintaining a satellite at altitude h_i , inclusive of ground stations and other support infrastructure, is $C(h_i)$. We assume it is first decreasing (for $h_i < \underline{h}$) and then increasing in altitude (for $h_i > \underline{h}$). This is explained by the countervailing facts that a higher altitude requires more lift energy at launch, but a lower altitude requires more fuel during operational lifetime to offset drag (De Pater and Lissauer (2015)).³ The annualized total cost of a constellation is $C(h_i)Q_i$.

Consumers purchase one unit of telecommunications service and are characterized by their preference for quality, θ . A type θ consumer has utility $u(\theta, i) = \theta x_i - p_i$ from purchasing satellite service from operator i , given service quality x_i and price p_i . We assume θ is uniformly distributed between $\underline{\theta}$ and $1 + \underline{\theta}$ in the population.

In the following sections, we construct the coupled physico-economic model from a combination of physical and economic first principles and empirical data.

¹This could be the case if, for example, the Leader has earlier access to a cost-reducing technology which eventually gets imitated. See Prescott and Visscher (1977) for more on the realism of sequential- vs simultaneous-move games in economics.

²We assume that the target population is consumers living in areas with low population density, who do not have access to the Internet by land-based means.

³The annualized unit cost of a satellite may well differ between the two competitors, either because of different design choices or because of different launch costs. We neglect these aspects below, due to the lack of precise data.

4.5.2 Model components and calibration

In this section we describe the components of the model, their calibration, and the solution concepts and algorithms in more detail.

4.5.2.1 Consumer demand and firm pricing

Consumers choose between purchasing one unit of service from the Leader or the Follower. The mass of N consumers is uniformly distributed in preference for satellite service quality, θ , over $[\underline{\theta}, 1 + \underline{\theta}]$. We assume that $\underline{\theta}$ is large enough, so that all targeted consumers will be willing to purchase satellite service.

Assume that, in equilibrium, the Leader offers a better quality than the Follower ($x_L > x_F$). We will show that the firm with the higher quality charges a higher price ($p_L > p_F$).⁴ The consumer who is indifferent between the two services has preference parameter θ^* such that

$$\theta^* x_L - p_L = \theta^* x_F - p_F, \quad (4.1)$$

which can be solved to yield

$$\theta^* = \frac{p_L - p_F}{x_L - x_F}. \quad (4.2)$$

If $\underline{\theta} < \theta^* < 1 + \underline{\theta}$, the demands for each service are

$$D_L = \left(1 - \frac{p_L - p_F}{x_L - x_F}\right) N, \quad (4.3)$$

$$D_F = \frac{p_L - p_F}{x_L - x_F} N. \quad (4.4)$$

The firms set prices simultaneously to maximize their individual profits,

$$\max_{p_L} \pi_L = p_L \left(1 + \underline{\theta} - \frac{p_L - p_F}{x_L - x_F}\right) N - C(h_L) Q_L, \quad (4.5)$$

$$\max_{p_F} \pi_F = p_F \left(\frac{p_L - p_F}{x_L - x_F} - \underline{\theta}\right) N - C(h_F) Q_F. \quad (4.6)$$

Their first-order conditions are

$$\left(1 + \underline{\theta} - \frac{p_L - 2p_F}{x_L - x_F}\right) N = 0, \quad (4.7)$$

$$\left(\frac{p_L - 2p_F}{x_L - x_F} - \underline{\theta}\right) N = 0, \quad (4.8)$$

$$(4.9)$$

⁴When qualities are identical, the pricing stage reduces to a Bertrand duopoly game between identical firms.

yielding (Nash equilibrium) prices

$$p_L = \frac{2 + \theta}{3} (x_L - x_F), \quad (4.10)$$

$$p_F = \frac{1 - \theta}{3} (x_L - x_F), \quad (4.11)$$

and demands

$$D_L = \frac{2 + \theta}{3} N, \quad (4.12)$$

$$D_F = \frac{1 - \theta}{3} N. \quad (4.13)$$

The optimized profits are

$$\pi_L = \frac{(2 + \theta)^2}{9} (x_L - x_F) N - C(h_L) Q_L, \quad (4.14)$$

$$\pi_F = \frac{(1 - \theta)^2}{9} (x_L - x_F) N - C(h_F) Q_F. \quad (4.15)$$

Notice that the equilibrium prices in equations 4.10 and 4.11 and equilibrium profits in equations 4.14 and 4.15 are increasing in the degree of quality differentiation between the two firms (i.e. p_i and π_i are increasing in $x_L - x_F$). Thus, constellation operators face incentives to differentiate their service offerings when choosing constellation design parameters which determine quality (altitude and size). This incentive raises the potential that firms over-differentiate in equilibrium.

4.5.2.2 Constellation service quality and cost

Service quality depends on the constellations' availability, coverage, latency, and bandwidth. We show below that they are determined by the constellation own altitude and size, but also by the other constellation altitude and size. For tractability, we assume that consumers are uniformly distributed over the Earth. See Osoro and Oughton (2021) for more detailed analysis of how non-uniformities in the geographical distribution of consumers affects the distribution of service quality at different locations. We give some brief intuition below for how these features may matter in a model like ours.

It is important to note that the distribution of consumers is non-uniform in three senses: geographically (population densities vary according to location on the globe), economically (consumer characteristics vary according to location on the globe), and temporally (the same location has different demand characteristics at different times). Since low-Earth orbit (LEO) satellites revolve around the Earth, designing a constellation to only serve specific customers at specific times (e.g. where and when geographic and economic features are favorable) is challenging if not impossible. Still, these non-uniformities may lead to deviations from our

modeling results in practice.

On one hand, our model implicitly accounts for some of these non-uniformities. The distribution of consumer preferences (i.e. θ) we use may already both represent economic heterogeneity *within* and *between* regions. For example, to the extent that high-WTP consumers are concentrated in particular areas (such as the global North), our model allows the firms to target those consumers through service offering characteristics. Similarly, to the extent that demand is lower at night, peak throughput (bandwidth per consumer) for subscribers may be higher than during the day, but average or worst-case peak throughput can still be calculated as in equation 4.25 below. On the other hand, some non-uniformities may affect characteristics that are integrated over physical space (e.g. bandwidth per consumer) more substantially. For example, a uniform distribution will overstate the bandwidth available in more-densely populated regions and understate bandwidth in more-sparsely populated regions. However, this is unlikely to substantially affect our main conclusions or estimates, given that the estimates are at the annual level and that constellation operators will likely target consumers living in sparsely populated areas not served by terrestrial means—a more homogeneously-distributed group than the consumer population at large.

Service quality

We assume that consumers evaluate telecommunications service from a constellation i along three dimensions: availability, latency and bandwidth. The willingness-to-pay (WTP) x_i of a representative consumer (i.e. with type $\theta = 1$) for a service with availability α_i , latency L_i , and bandwidth S_i will have the form

$$x_i = F(\alpha_i)G(L_i, S_i), \quad (4.16)$$

where F is a function reflecting the fraction of WTP preserved given partial service availability and G is a function reflecting WTP for fully-available service. We assume that F and G satisfy the following conditions:

1. Consumers will be willing to pay nothing for service which is never available: $F(0) = 0$;
2. Consumers prefer greater availability: $F'_\alpha(\alpha) > 0$ for all $\alpha \in [0, 1]$;
3. A representative consumer (i.e. with type $\theta = 1$) will be willing to pay $G(L, S)$ when service with latency L and bandwidth S is always available : $F(1) = 1$;
4. Consumers prefer less latency and higher bandwidth: $G'_L(L, S) < 0$ and $G'_S(L, S) > 0$ for all $L \geq 0$ and $S \geq 0$.

We assume consumers have positive WTP for a service with latency no greater than \bar{L} , with bandwidth preference parameter a_S and latency preference parameter a_L . These parameters

are calibrated such that a typical consumer's WTP for the service is 1500 \$/year. We use the following specifications:

$$F(\alpha) = \alpha^2, \quad (4.17)$$

$$G(L, S) = a_L(\bar{L} - L) \frac{S^2}{a_S + S^2}, \quad (4.18)$$

where $\alpha \in [0, 1]$, $L \geq 0$, and $S \geq 0$. The specification of F implies that consumers strongly prefer higher availability. The specification of G implies that, ceteris paribus, consumers have constant marginal WTP for lower latency and a diminishing marginal WTP for larger bandwidth. Latency and bandwidth are assumed to contribute multiplicatively to overall WTP. That is, while consumers are willing to substitute between latency and bandwidth to some extent, there are also complementarities between the two. a_S has units of bandwidth squared ((Mb/s)²), \bar{L} has units of latency (ms), and a_L has units of WTP per unit latency (\$/ms).

We calibrate a_L , a_S and \bar{L} to be consistent with the following data:

1. A standard internet service provides a latency of 25 ms, a bandwidth of 75 Mb/s, and is available 100% of the time;
2. A representative consumer is willing to pay a maximum of 1500 \$/y. to subscribe for a standard internet service;
3. The willingness to pay for a lower latency is about 6 \$/year/ms (Liu, Prince and Wallsten, 2018);
4. The willingness to pay for an increased bandwidth amounts to 168 \$/year, from 4 Mb/s to 10 Mb/s, and 288 \$/year, from 10 Mb/s to 25 Mb/s (Liu, Prince and Wallsten, 2018).

The values of a_L , a_S , and \bar{L} chosen to approximately match these targets are listed in Table 4.3. Figure 4.8 gives a graphical representation of the marginal WTP of a representative consumer ($\theta = 1$) for a fully-available ($F \equiv 1$) service supplying latency L (x-axis) and bandwidth S (y-axis). Later, we will conduct a sensitivity analysis with respect to preference parameters a_L , a_S and \bar{L} . In order to obtain relevant and comparable outcomes, we will restrict our attention to sets of parameters satisfying requirements 1, 2 and 3 above.

Earth coverage

We assume that each satellite of a constellation with average altitude h_i can cover a circle of radius $h_i \tan(\phi/2)$ and area $\pi h_i^2 \tan^2(\phi/2)$, where ϕ is the average angle of the beam from

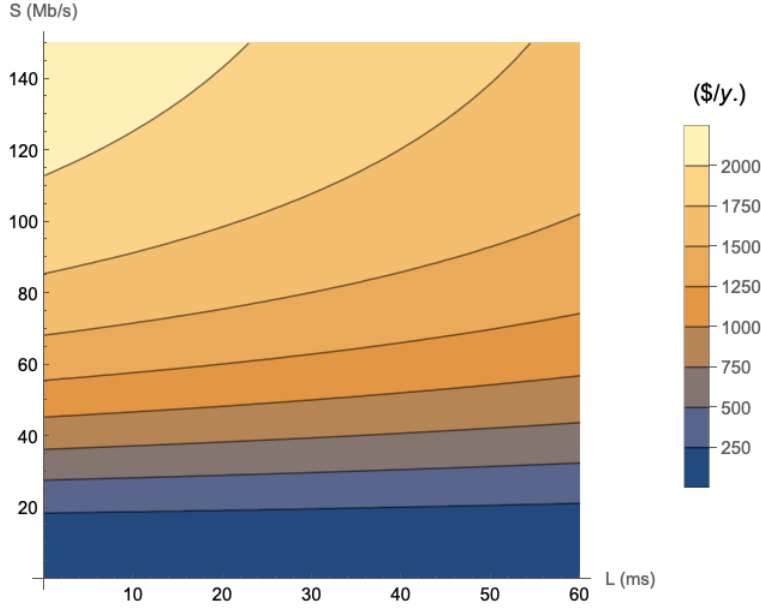


Figure 4.8: Maximum willingness to pay of a representative consumer ($\theta = 1$). The contour map reflects that greater bandwidth is a good while greater latency is a bad.

the satellite to the surface. The surface area of the Earth is πR^2 , so the minimum number of satellites needed to fully cover the Earth at any instant is approximately

$$\underline{Q}(h_i) = \frac{R^2}{h_i^2 \tan(\phi_i/2)^2}. \quad (4.19)$$

The constellation consists of Q_i satellites. However, at a given instant, due to avoidance maneuvers, $\beta_i Q_i$ satellites are “turned off” (not providing service) on average (see below for the definition and calculus of β_i). If the remaining constellation is smaller than the minimum covering number ($(1 - \beta_i)Q_i < \underline{Q}(h_i)$), each operational satellite will serve an area of $\pi h_i^2 \tan(\phi/2)^2$ and the system will have gaps in coverage (i.e. areas which are not covered at some point of the day). If the remaining constellation is larger than the minimum covering number ($(1 - \beta_i)Q_i \geq \underline{Q}(h_i)$), it will have full coverage. Each operational satellite then covers a circle with radius $R/\sqrt{(1 - \beta_i)Q_i}$ and area $\pi R^2/((1 - \beta_i)Q_i)$.

The fraction of the Earth covered at any instant is

$$\alpha_i = \begin{cases} (1 - \beta_i)Q_i/\underline{Q}(h_i) & \text{if } (1 - \beta_i)Q_i < \underline{Q}(h_i) \\ 1 & \text{if } (1 - \beta_i)Q_i \geq \underline{Q}(h_i). \end{cases} \quad (4.20)$$

We calibrate the average beam angle ϕ so that the minimum covering numbers at the approximate mean altitudes of Starlink and OneWeb—550 km and 1,200km—are close to full coverage at their approximate current (Starlink, 3,351 satellites) and planned (OneWeb, 648 satellites) sizes. The value is listed in Table 4.2.

Latency

Consider the area that an operational satellite services as a circle of radius r_i centered at its vertical. Average signal latency is determined primarily by the average distance between consumers in the market and the satellite. Assuming that consumers are uniformly distributed over this area, the average distances are the lengths of the straight lines connecting them to the satellite.

From the Pythagorean theorem, the distance between a satellite at altitude h_i and a consumer located at a distance x of the center of the market is $\sqrt{x^2 + h_i^2}$. Integrating over the radius of the market under a spatially-uniform consumer distribution, we obtain an average distance of

$$d_i = \int_0^{r_i} \frac{\sqrt{x^2 + h_i^2}}{r_i} dx \quad (4.21)$$

$$= \frac{h_i}{2} \left[\sqrt{1 + \left(\frac{r_i}{h_i}\right)^2} + \frac{h_i}{r_i} \ln \left(\frac{r_i}{h_i} + \sqrt{1 + \left(\frac{r_i}{h_i}\right)^2} \right) \right], \quad (4.22)$$

where

$$r_i = \begin{cases} h_i \tan(\phi/2) & \text{if } (1 - \beta_i)Q_i < \underline{Q}(h_i) \\ R/\sqrt{(1 - \beta_i)Q_i} & \text{if } (1 - \beta_i)Q_i \geq \underline{Q}(h_i). \end{cases} \quad (4.23)$$

If the signal travels at average speed v , we obtain the average time-of-flight for a single trip as d_i/v . Assuming that the signal makes λ trips and the electronic systems introduce a minimum latency of μ , the average latency for a constellation at altitude h_i and size Q_i is then

$$L_i = \lambda 10^3 d_i/v + \mu. \quad (4.24)$$

We calibrate λ and μ so that the implied latencies for the Starlink and OneWeb constellations are consistent with publicly available data on their service offerings (Ookla, 2022, Brodtkin, 2019). The parameter values are listed in Table 4.2. The implied latencies for Starlink and OneWeb are about 34 ms and 38 ms, respectively.

Bandwidth

An operational satellite in constellation i provides average bandwidth of κ Mb/s. Constellation i therefore supplies total bandwidth of $\kappa(1 - \beta_i)Q_i$ shared among all covered subscribers. Given a coverage rate of α_i , only $\alpha_i D_i$ consumers can be active at the same time among the D_i subscribers to constellation i . Therefore the throughput at peak load for a subscriber

receiving service will be equal to

$$S_i = \frac{\kappa(1 - \beta_i)Q_i}{\alpha_i D_i}. \quad (4.25)$$

For tractability, we assume consumers anticipate bandwidth S_i per equation 4.25 under equilibrium demand (equations 4.12 and 4.13), thus taking the behavior of other consumers as given. Bandwidth for each constellation then simplifies to

$$S_L = \frac{3\kappa(1 - \beta_L)Q_L}{2\alpha_L(2 + \underline{\theta})N}, \quad (4.26)$$

$$S_F = \frac{3\kappa(1 - \beta_F)Q_F}{\alpha_F(1 - \underline{\theta})N}. \quad (4.27)$$

We calibrate the average bandwidth per satellite κ so that the implied peak-load throughput per subscriber for a constellation like Starlink (most satellites currently located near 550 km altitude, full coverage, 3,351 satellites and 1,000,000 subscribers) is consistent with publicly available data on Starlink (Ookla, 2022) for North America. The parameter value is listed in Table 4.2. The implied peak-load throughput per subscriber is about 84 Mb/s.

Satellite unit costs

The unit cost of a satellite includes the costs of manufacture, launch, and operations during lifetime, inclusive of ground stations. We let $C(h_i)$ be the annualized unit cost of a satellite. The annualized cost of a constellation of Q_i satellites is equal to $C(h_i)Q_i$.

Physical principles (e.g. the rocket equation) and empirical data support modeling the launch cost of a satellite as increasing in its altitude. There is less guidance on the operation cost during lifetime. We will approximate the annualized unit cost function as

$$C(h_i) = c - dh_i + \frac{e}{2}h_i^2, \quad (4.28)$$

where all parameters c , d and e are assumed positive. This specification implies that the annualized cost of a satellite is strictly convex and reaches a minimum at $\underline{h} = d/e$. We set the cost-minimizing altitude \underline{h} to 500 km.

We calibrate the parameters of $C(\cdot)$ to match publicly available information about unit launch costs for the Starlink and OneWeb megaconstellations. Following Osoro and Oughton (2021) and public statements by SpaceX COO Gwynne Shotwell (Wang, 2019), we assume the cost of a reference satellite with a 5-year operational life is on the order of 500,000 \$, with additional operational and support infrastructure costs on the order of 125,000 \$. We thus approximate the annualized cost of a satellite at the cost-minimizing altitude \underline{h} as 150,000 \$. Taken together, these figures imply that the annualized cost of building, launching, operating, and supporting a satellite at 550 km (Starlink) and at 1,200 km (OneWeb) altitudes are 152,500 \$ and 640,000 \$ respectively. The parameter values are listed in Table 4.3.

4.5.2.3 Avoidance maneuvers and service availability

To avoid collisions, satellites in constellation i must maneuver in response to at least some conjunctions. These maneuvers are an opportunity cost for operators, as they reduce their constellations’ operational service time. To keep the model tractable and focus on economic behavior, we assume that all maneuvers are successful and result in no collisions.⁵

We assume that satellites will maneuver if and only if the conjunction is predicted to occur at or within a “maneuver safety margin” of ρ kilometers. As mentioned in the main text, this parameter may depend on technical, behavioral and regulatory factors, such as the constellations slotting architectures, the positional uncertainty in the object’s trajectory (Arnas et al., 2021, D’Ambrosio et al., 2022), the operators’ risk aversion and/or the implementation of avoidance guidelines coordinated internationally (IADC, 2017).⁶

Following prior literature (Lewis et al., 2009, Lifson et al., 2022, Talent, 1992), we model the probability $\delta(h)$ that any two satellites orbiting in a common shell at mean altitude h have a maneuver-inducing conjunction using kinetic gas theory as⁷

$$\delta(h) = \pi \frac{(2\rho)^2 v(h)}{V(h)}, \quad (4.29)$$

where

$$v(h) = \sqrt{\frac{GM}{R+h}} \quad (4.30)$$

is the velocity of an object in a circular orbit at altitude h , GM is the geocentric gravitational constant and R is the radius of the Earth, and

$$V(h) = \frac{4}{3}\pi ((R+h+\Delta)^3 - (R+h-\Delta)^3) \quad (4.31)$$

is the volume of a circular shell of thickness 2Δ at altitude h above the Earth’s surface. Satellites in different shells are assumed to have no conjunctions.

The *expected* number of maneuvers n_i that constellation i will have to perform per day is calculated by adding the number of conjunctions involving two satellites from constellation i (internal congestion) and one satellite from constellation i with any other objects in the same orbital shell (external congestion). Knowing that the constellation i operates Q_i satellites at

⁵Failed maneuvers would require explicit analysis of debris and collision risk dynamics—an important extension for future research.

⁶While in principle each object type could have a different safety margin (and even conjunction pair-specific safety margins), given the limited publicly available data on maneuver behavior we assume all objects use a common safety margin.

⁷Note that prior literature (Lewis et al., 2009, Lifson et al., 2022, Talent, 1992) calculates the probability of *collision*, as a function of the radii of the two objects, while we calculate the probability of *conjunction*, as a function of their maneuvering safety margins ρ .

altitude h_i , we obtain:

$$n_i = 24 \times 60 \times 60 \delta(h_i) \frac{Q_i (Q_i + Q_{-i})}{2} \quad (4.32)$$

where Q_{-i} represents the number of *other* objects in the same shell and the factor of $1/2$ reflects symmetric turn-taking behavior. We define the constellation system’s daily *maneuver burden* as $n_L + n_F$.

We calibrate ρ to match open-source analysis of Starlink maneuver behaviors in Lewis (2022). By the end of 2022, Lewis (2022) utilized reporting by SpaceX and publicly available data to infer that Starlink satellites were collectively conducting around 75 maneuvers per day. Data from USSPACECOM (2022) indicates that as of December 26th, 2022 there were approximately 5616 objects total (3015 of them Starlink satellites) within the 35 km shell centered at 550 km (the mean altitude of Starlink). This implies that ρ must solve $n_i = 75$, given $h_i = 550$, $Q_i = 3015$ and $Q_i + Q_{-i} = 5616$, giving a value of approximately $\rho = 0.150$ km. The value of ρ can be interpreted as follows: “if two satellites are predicted to approach within about 0.300 kilometers of each other then their operators commit to one of them maneuvering, each taking turns being the one to maneuver.” Figure 4.9 gives a graphical representation of the numbers of maneuvers per day for a constellation at altitude h (x-axis) and size Q (y-axis), considering only internal conjunctions. Note that since we predict close approaches using kinetic gas theory, our estimated safety margin may be smaller than those used in practice. This is because kinetic gas theory assumes objects move randomly, whereas in reality satellite trajectories are not random. Since we maintain this assumption throughout, the magnitudes of welfare gains from optimal orbit use will likely be unaffected.

Letting τ be the average operational time (hours) lost per avoidance maneuver which reduces service,⁸ the fraction of operational time that constellation i loses to maneuvers (“congestion”) is:

$$\beta_i = \frac{\tau n_i}{24 Q_i}. \quad (4.33)$$

In both the equilibrium and optimal solutions under the benchmark calibration, constellations are spaced far enough apart that there are no conjunctions between operational satellites in different constellations.

4.5.2.4 Solution concepts and algorithms

We apply two solution concepts: a “duopoly equilibrium” and an “optimal plan”. The duopoly equilibrium predicts the allocation of orbital space if profit-maximizing firms compete in the two-stage game described in section 4.5.2.1 and below. The optimal plan predicts

⁸Not all maneuvers necessarily reduce service time for the constellation as a whole. For example, the maneuver may involve satellites that are not transmitting or receiving signals and *a priori* not scheduled to do so till after the maneuver’s duration. Similarly, the constellation may have a redundant satellite ready for that situation, or the maneuver may have been pre-planned with coverage arranged.

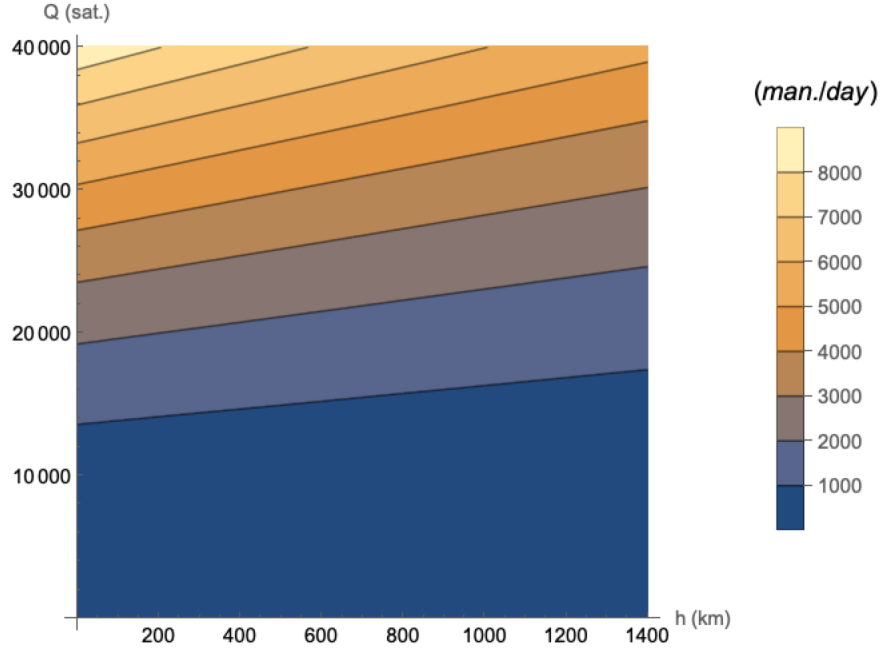


Figure 4.9: Number of maneuvers per day (internal conjunctions only). The contour map reflects that internal conjunctions increase in constellation size Q_i at an increasing rate as the maneuver distance ρ increases.

the allocation if constellations were designed by a benevolent planner to maximize global economic welfare from constellation telecommunications services.

We assume everywhere that the market is fully served, i.e. no consumers are left without telecom service. In equilibrium, this assumption is justified if it is profitable to serve all potential customers. In the optimum, this assumption is justified if it is socially beneficial to serve all consumers (i.e. equity of access). This assumption is satisfied in the equilibrium and optimum of the benchmark results presented in the main text.

Duopoly equilibrium

Firms first play a Stackelberg game of sequentially choosing altitude and constellation size. As described earlier, the Leader moves first in choosing an altitude and constellation size. In doing so they anticipate the Follower's optimal response in terms of altitude and constellation size as well as the equilibrium of the pricing subgame described in Section 4.5.2.1. The Follower best-responds to the Leader's choice anticipating only the price subgame equilibrium. Formally, using the solutions to the price equilibrium (equations 4.14 and 4.15), the Follower solves

$$\max_{h_F, Q_F} \pi_F = \frac{(1 - \theta)^2}{9} (x_L - x_F) N - c(h_F) Q_F, \quad (4.34)$$

taking (h_L, Q_L) as given, with x_L and x_F as defined in 4.16.

The solution to equation 4.34 gives the Follower's best-response functions, $h_F(h_L, Q_L)$

and $Q_F(h_L, Q_L)$. The Leader internalizes the Follower’s behavior and solves

$$\max_{h_L, Q_L} \pi_L = \frac{(2 + \theta)^2}{9} (x_L - x_F) N - c(h_L) Q_L, \quad (4.35)$$

anticipating $h_F(h_L, Q_L)$ and $Q_F(h_L, Q_L)$, with x_L and x_F as defined in 4.16.

Below, we restrict our attention to equilibria satisfying the following incentive compatibility constraints:

$$\underline{\theta} x_F - p_F \geq 0, \quad (4.36)$$

$$\pi_F \geq 0. \quad (4.37)$$

The first condition states that the consumer with the lowest valuation on telecom service gets non-negative utility from subscribing to the Follower’s constellation. The second condition states that the Follower earns non-negative profits from staying in the market.

A duopoly equilibrium is a vector of choices for each firm, (h_L, Q_L, p_L) and (h_F, Q_F, p_F) , and an indifferent consumer θ^* , such that no firm has an incentive to change their strategies, the indifferent consumer gains equal utility from either firm’s service, all consumers have positive utility, and the Follower stays in the market (i.e. a joint solution to the system defined by 4.1, 4.5, 4.6, 4.34, 4.35, 4.36, and 4.37).

Social optimum

The planner seeks to maximize total economic welfare from constellation deployment, i.e. consumer surplus net of constellation production and environmental damage costs. To this end they may choose to deploy one or two constellations. We refer to these choices in the main text as “public utility constellations”. A single very large constellation may be able to provide a high quality service to all consumers at a single low altitude (low latency and high bandwidth), but at the cost of more congestion and avoidance maneuvers. Two smaller constellations can provide differentiated services to better match varied consumer preferences at lower cost. We allow the planner to choose between welfare-maximizing one- and two-constellation architectures to determine the overall economically-optimal constellation design.

We assume environmental damage costs are proportional to the total number of satellites in orbit. The environmental damage cost of an additional satellite, denoted as f , captures various impacts throughout its lifecycle: damages from launch emissions and debris; collision risk, debris formation, and interference with astronomical observations (Adilov, Alexander and Cunningham, 2015, Massey, Lucatello and Benvenuti, 2020, Rao, Burgess and Kaffine, 2020, Rouillon, 2020, Venkatesan et al., 2020); contributions to climate change and ozone depletion during reentry; and potential damage to human and physical capital upon landing (Byers et al., 2022, Ryan et al., 2022). Notably, these costs are externalities, overlooked by private constellation operators (Adilov, Alexander, and Cunningham, 2022, Lawrence et

al., 2022). With limited data on the full extent of damages from these externalities, further research is imperative to better understand and address these issues. We set the value of f to zero in our main scenarios and conduct sensitivity analysis over the magnitude of damages to understand how they impact optimal and equilibrium orbital allocations.

When the planner allocates orbital space to one constellation, they solve

$$W_1 = \max_{h, Q} N \int_{\underline{\theta}}^{\underline{\theta}+1} \theta x \, d\theta - (C(h) + f) Q. \quad (4.38)$$

When the planner allocates orbital space to two constellations, they solve

$$W_2 = \max_{h_L, Q_L, h_F, Q_F, \theta^*} N \int_{\theta^*}^{\underline{\theta}+1} \theta x_L \, d\theta + N \int_{\underline{\theta}}^{\theta^*} \theta x_F \, d\theta \quad (4.39)$$

$$- C(h_L) Q_L - C(h_F) Q_F - f(Q_L + Q_F). \quad (4.40)$$

Both problems are subject to all the physical constraints/functions as described earlier. The planner chooses the better of the two optimized constellation designs, solving

$$W = \max\{W_1, W_2\}. \quad (4.41)$$

We assume that the planner seeks to serve all consumers, so internalizes 4.36 as a constraint. However, the planner controlling two constellations has an additional degree of freedom: by letting the size of the constellation serving the lower end of the market shrink and moving the threshold θ^* , the two-constellation planner is able to reduce service to consumers with lower valuations. Thus, while the planner controlling one constellation is constrained to provide equitable service to all even if it reduces aggregate welfare, the planner controlling two constellations can segment the market as necessary to maximize aggregate welfare.

An optimal plan is a vector of constellation design characteristics $((h, Q)$ if $W_1 \geq W_2$ and (h_L, Q_L, h_F, Q_F) otherwise) which solves equation 4.41. If $W_2 > W_1$ then the optimal plan includes an indifferent consumer θ^* to solve equation 4.40.

Algorithms

To solve for the duopoly equilibrium and social optimum, we first generate a grid over possible values of (h_L, Q_L, h_F, Q_F) .⁹ We then compute the value of each constellation and total economic welfare with two constellations (i.e. the objective function being maximized in program 4.40) at each grid point. For the decentralized equilibrium, we then compute the Follower's profit-maximizing choices of (h_F, Q_F) conditional on the Leader's choices, i.e. we

⁹We describe the altitude grid construction in more detail in section .

Algorithm 4.1 Algorithm to calculate decentralized equilibrium

Generate $grid(h_L, Q_L, h_F, Q_F)$.

Calculate $\pi_L, \pi_F, W, \theta x_F - p_F$ at each grid point. Discard all points which do not satisfy conditions 4.36 and 4.37.

Calculate $\text{argmax}_{h_F, Q_F} \pi_F$ for each value of (h_L, Q_L) . Call these (h_F^e, Q_F^e) .

Calculate $\text{argmax}_{h_L, Q_L} \pi_L$ assuming Follower chooses (h_F^e, Q_F^e) in response. The profile $(h_L^e, Q_L^e, h_F^e, Q_F^e)$ is the Stackelberg equilibrium.

Set firms' prices according to equations 4.10 and 4.11 to reflect equilibrium in the simultaneous-move pricing subgame.

calculate the Follower's best response $(h_F(h_L, Q_L), Q_F(h_L, Q_L))$ for each choice (h_L, Q_L) the Leader could make, conditional on the incentive compatibility conditions 4.36 and 4.37 being satisfied. Next, we compute the Leader's optimal choice of (h_L, Q_L) given the Follower's best response to that choice, and select the choice which maximizes the Leader's profits. Finally, firms' prices are set to solve the simultaneous-move game described in section 4.5.2.1, i.e. per equations 4.10 and 4.11. This is described more precisely in Algorithm 4.1.

Solving the planner's problem is more straightforward. We solve problems 4.38 and 4.40 using Generalized Simulated Annealing (GSA) (Tsallis and Stariolo, 1996) as implemented in the R package GenSA (Xiang et al., 2013), and select the one with the highest objective function value. This is the constellation design that maximizes economic welfare. In this setting GSA is preferable to methods such as Nelder-Mead or BFGS as the physical equations for service quality, latency, and coverage include non-differentiable points, and GSA provides better guarantees of finding the global optimum regardless of initial value. However, its runtime precludes use in the duopoly equilibrium problem where multiple nested GSA calls would be required. The objective surface for the planner's problem in the two-constellation case also features multiple solutions with near-identical welfare levels. To address instability in sensitivity analysis caused by multiple solutions with approximately equal welfare levels, we restrict the solver to focus on solutions where the constellation serving the upper end of the market is at a lower altitude than the one serving the lower end of the market. This has no effect on the solution in the benchmark calibration, and makes the solution paths for sensitivity analyses smoother without reducing economic welfare.

Orbital shell discretization

For tractability and following prior work, we discretize orbital space into a series of non-overlapping shells. For the duopoly equilibrium, we construct a grid of altitude values beginning at 200 km and ending at 900 km and use it as described in Algorithm 4.1. For the optimum, we constrain the GSA solver to a numerically-stable portion of the 200-900 km region identified through testing. For both the equilibrium and the optimal plan we apply external congestion only if the constellations are within 35 km of each other, consistent with

the discretization used in Lifson et al. (2022) and the announced spacings of Starlink and Kuiper (which are set to be 50 km apart in the latest FCC filings).

Parameter values

Tables 4.2 and 4.3 lists the parameter values, parameter units, and a brief description of the calibration strategy where applicable. We set the number of consumers purchasing service, N , to 10,000,000 to reflect the assumption of a more-mature sector in the near future. Current LEO constellation subscribers globally are on the order of 1,000,000 (Jewett, 2022). Note that we are not making a forecast of demand for constellation services from any particular operator, rather choosing a market size to reflect a particular scenario.

4.5.3 Sensivity analysis

4.5.3.1 Market size and maneuver safety margin

This figure shows the monetary value of the welfare gain generated by optimal utility constellations as a function of target population size values. Figure 4.10 shows the dollar value of welfare gain generated by the optimal public utility constellations over values of size of targeted population (N) and maneuver safety margin (ρ).

As mentioned in the main text, the monetary value of the gain from a two-constellation public utility system is increasing in N (holding ρ constant) even as the percentage gain decreases (main text Fig. 5). Figure 4.11 illustrates this point: holding ρ constant at the benchmark level and varying N , the welfare gain from moving from duopoly to a two-constellation system is roughly \$1 billion. At 20 million consumers, the gain is roughly \$2 billion.

4.5.3.2 Preference parameters

We conduct sensitivity analysis over preference parameters a_L , \bar{L} , and a_S , while maintaining the maximum and marginal willingness to pay for lower latency as in the benchmark calibration, given a standard internet service (25 ms latency, 75 Mb/s bandwidth available full time). The sensitivity analysis thus goes through the set of parameters satisfying these conditions:

- Same maximum WTP:

$$a_L(\bar{L} - L)\frac{S^2}{a_S + S^2} = 9(275 - L)\frac{S^2}{3025 + S^2} \quad (4.42)$$

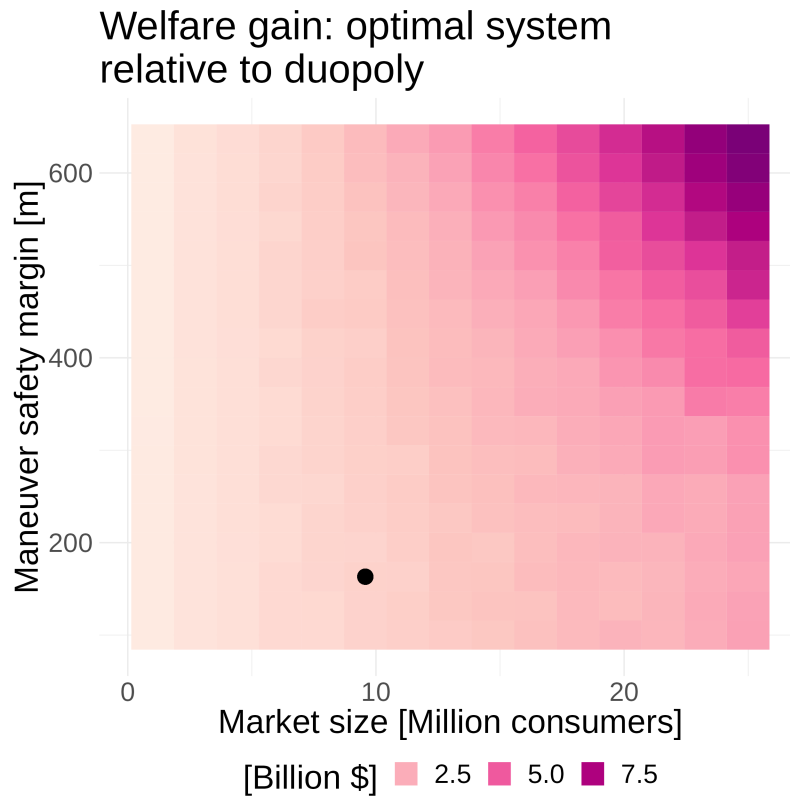


Figure 4.10: Dollar value gain in economic welfare from the economically-optimal two-constellation public utility system relative to the duopoly equilibrium across population size and maneuver safety margin. The black dot shows the benchmark calibration.

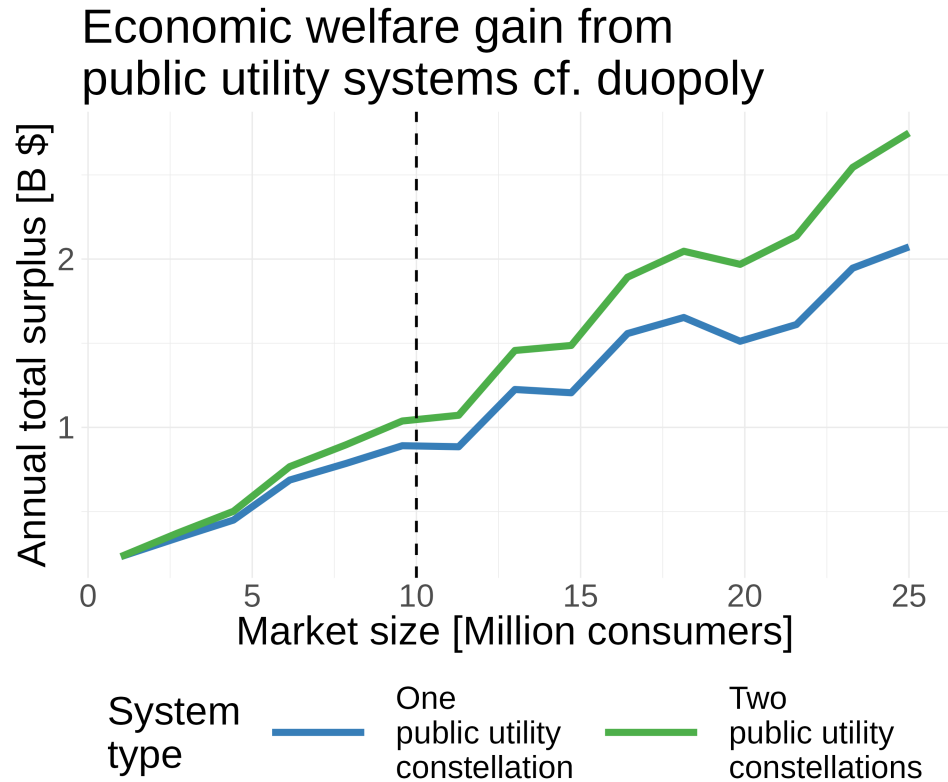


Figure 4.11: Dollar value gain in economic welfare from the economically-optimal two-constellation public utility system relative to the duopoly equilibrium across population size, holding maneuver safety margin constant. The dashed line shows the benchmark calibration.

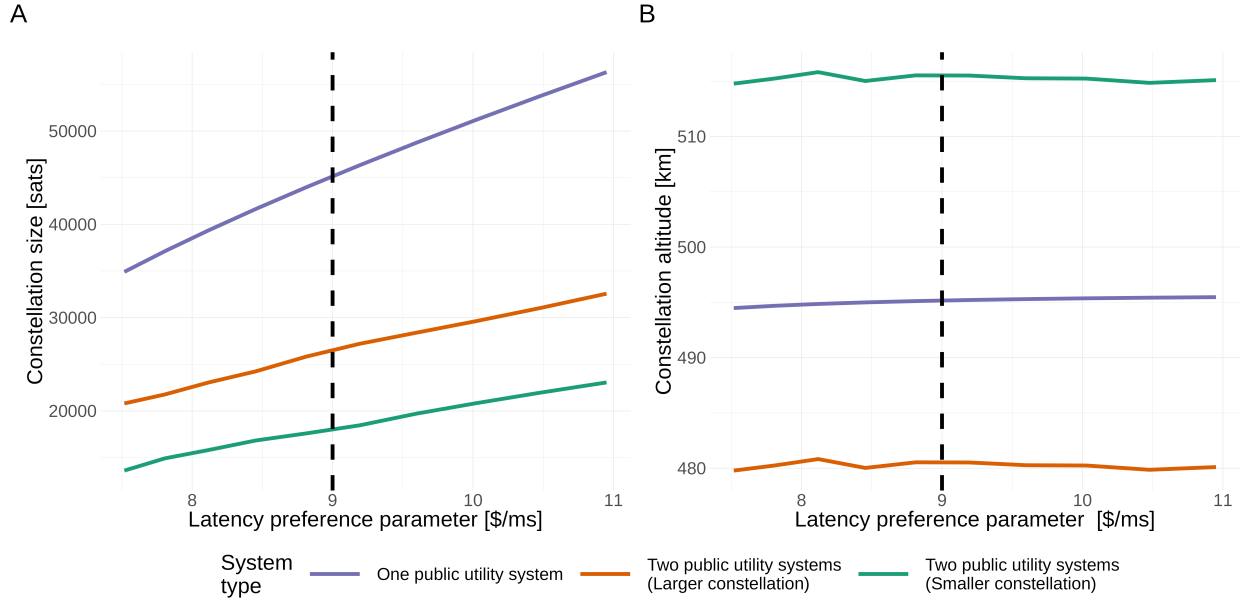


Figure 4.12: Change in number of satellites for public utility constellations as latency preference parameter a_L varies subject to equations 4.44 and 4.45. The dashed line shows the benchmark calibration.

- Same marginal WTP for latency improvements:

$$a_L \frac{S^2}{a_S + S^2} = 9 \frac{S^2}{3025 + S^2} \quad (4.43)$$

when $L = 25$ and $S = 75$. This implies that:

$$\bar{L} = 275 \quad (4.44)$$

$$a_L = 9 \frac{a_S + 5625}{8650}. \quad (4.45)$$

That is, in order to maintain the targets we set for maximum and marginal WTP, we must hold one parameter (\bar{L}) at the benchmark level and co-vary a_L and a_S as dictated by equation 4.45. We conduct the sensitivity analysis over $a_S \in [40^2, 70^2]$.

The total constellation sizes increase at a decreasing rate as a_L and a_S increase. The altitude also increases, though at a very slow rate. A higher preference for service quality (of which bandwidth is an important part) can justify decreased availability due to larger sizes at roughly the same altitude.

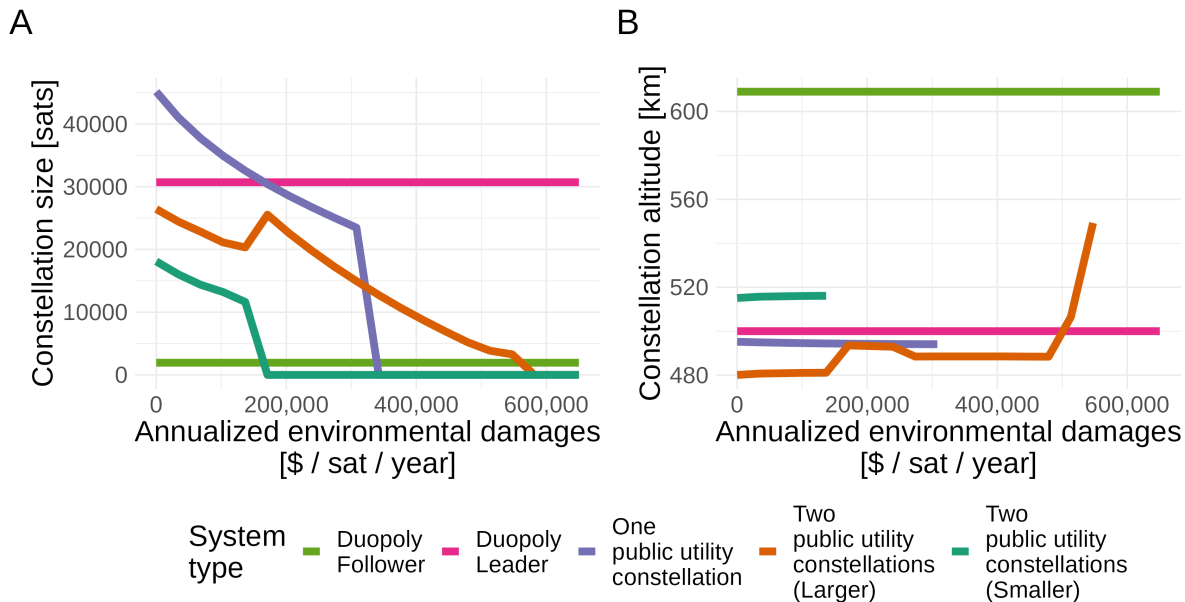


Figure 4.13: Change in total number of satellites for public utility constellations as total environmental damages from orbit use increase. In the benchmark calibration these damages are set to zero.

4.5.3.3 Environmental damages

We conduct sensitivity analysis over the magnitude of environmental damages, f , to identify how the optimal allocations change in response to these external costs. We find that total environmental damages on the order of \$150,000 are sufficient to make the public utility constellation sizes match the duopoly sizes, though the orbital space allocations remain different. Figure 4.7 in the main text shows the total number of satellites and the threshold at roughly \$150,000 in total environmental damages. Figure 4.13 shows the size and location allocations by constellation.

The single public utility constellation abruptly goes to zero at roughly \$330,000 in total environmental damages. This is related to the equity constraint discussed in section , i.e. equation 4.36. The planner controlling a single constellation must provide equitable service to all consumers. When the environmental damages become high enough there is no way to provide such service while also generating surplus sufficient to cover the costs of the system. That is, the service quality becomes bad enough that consumers with a low valuation will prefer to not have it. The planner therefore ceases to provide constellation service once the environmental damages cross this threshold, since it is unable to provide all consumers with desirable service. The two-constellation planner is not similarly constrained. In this case, the planner ceases deployment of the smaller constellation once the \$150,000 damages threshold is crossed, progressively reducing the size of the remaining system as well as the market it serves. This ensures that the system provides positive net benefits to the consumers it serves.

Parameter	Value	Description	Units	Source
Physical constants				
R	6371	Radius of the Earth.	$[km]$	
GM	3.986×10^5	Geocentric gravitational constant.	$[\frac{km^3}{s^2}]$	
v	3×10^5	Speed of light in vacuum.	$[\frac{km}{s}]$	
Technical parameters				
ϕ	0.4	Average beam angle.	$[radians]$	Calibrated to make minimum coverage numbers at 550 km and 1200 km altitudes consistent with Starlink and OneWeb sizes.
λ	2	Time-of-flight multiplier.	$[unitless]$	Reflects trips from satellite to ground station to consumer.
μ	30	Minimum hardware and network latency.	$[ms]$	Lower end of published latencies for Starlink and OneWeb.
κ	2.5×10^4	Peak throughput coefficient.	$[\frac{Mb/s}{satellite}]$	Calibrated to be consistent with average download speed for Starlink in North America near end of 2022 ($\approx 1e7$ subscribers).
τ	2	Average satellite service time lost per maneuver.	$[\frac{h}{maneuver}]$	Assumption.
ρ	0.150	Maneuver safety margin.	$[km]$	Calibrated to be consistent with analysis in Lewis (2022) and object count data as of 26-12-2022 from USSPACECOM (2022).
Δ	17.5	Orbital shell thickness.	$[km]$	Consistent with MOCAT altitude bin discretization used in Lifson et al. (2022).

Table 4.2: Table of calibrated physical and technical parameter values.

Parameter	Value	Description	Units	Source
Economic parameters				
a_L	9	Willingness-to-pay for lower latency.	$[\frac{\$/year}{ms}]$	From Liu, Prince and Wallsten (2018). Calibrated to match 6 \$/year/ms WTP for lower latency.
a_S	3025	Willingness-to-pay for higher bandwidth.	$[(\frac{\$/year}{Mb/s})^2]$	From Liu, Prince and Wallsten (2018). Calibrated to match 168 \$/year WTP for bandwidth increase from 4 Mb/s to 10Mb/s and 288 \$/year WTP for increase from 10 Mb/s to 25 Mb/s.
\bar{L}	275	Latency which makes consumers indifferent between status quo (no service) or a subscription with 25 ms latency and 75 Mb/s bandwidth for 1500 \$/year	$[ms]$	
c	4×10^5	Annualized satellite unit cost.	$[\frac{\$/year}{satellite}]$	Calibrated to be consistent with Table 2 of Osoro and Oughton (2021) and public statements by Gwynne Shotwell (Wang, 2019).
d	1000	Annualized satellite unit cost / gross rate with altitude.	$[\frac{\$/year}{satellite-km}]$	Same as above, also calibrated to imply cost-minimizing altitude of 300 km.
e	2	Annualized satellite unit cost / gross rate with altitude squared.	$[\frac{\$/year}{satellite-km^2}]$	Same as above.
$\bar{\theta}$	0.5	Utility parameter for consumer with lowest WTP for satellite service.	$[unitless]$	Normalization.
N	10^7	Total number of targeted consumers.	$[people]$	Reflects mature market.

Table 4.3: Table of calibrated economic parameter values.

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