Estimation of costs and benefits of debris mitigation

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Abstract

Space debris is an ever escalating problem that is increasing the orbital scarcity and threatening its sustainability. In this document, we present a model for the market of satellite services where firms' activity imposes an external cost on other firms due to the risk of collision and debris accumulation. We evaluate the equilibrium outcomes depending on the number of competitors, which affects the probability of collision. Extensions of the model include the consideration of different types of satellites in terms of weight and purpose. Our model suggests policy recommendations for the outer space debris and how a possible fiscal policy can promote debris mitigation in LEO (Low Earth Orbit).

Keywords: *debris mitigation, space economics, satellites, probabilty of collision*

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1.1 Introduction

Space debris, objects that are no longer in use or function in the Earth orbit, represents a serious risk to spacecrafts and new mission satellites and potentially an environmental problem due to the emission of pollutants. It is a negative externality generated by launchers and damaged satellites which is already challenging the sustainability of human activity in the outer space. While at the onset of space activity the resources seemed to be unlimited, nowadays the access to the limited geo-stationary (GEO) and low (LEO) orbital slots is rival and face the tragedy of the commons, as current regulation cannot implement rigid systems of exclusion.

According to a study presented in April 2021 at the 8th European Conference on Space Debris, the problem has been underestimated, and the amount of space junk in orbit could, in a worst-case scenario, grow 50-fold by 2100. The number of debris objects estimated by statistical models to be in orbit (as of January 2021) is: 34,000 objects greater than 10 cm, 900,000 objects from 1 cm to 10 cm and 128 million objects from 1 mm to 1 cm (European Space Agency).

Debris accumulation has a multiplicative effect, the more collision fragments there are, the more collisions will occur, with the risk that the entire population be reduced to subcritical sizes. If the amount of space debris follows the tendency of recent years, eventually it will reach a tipping point, known as the Kessler syndrome, that would prevent any space activity.

The current economic cost of space debris is multidimensional, in the sense that it currently generates economic losses when incidents occur, thus hampering the normal functioning of satellites and, at the same time, it may further impede the development of new opportunities if a critical level of congestion is reached or if the capacity of orbits decreases. Our approach to this problem is to empirically approximate the cost of space debris when launching a satellite and test the possibilities for policy intervention. We build a model to analyze the impact of increasing space activity, estimate the parameters of the model and obtain the external costs imposed by space activity and the benefits of space debris mitigation.

So far, the contribution of economic analysis to the understanding of the problem has been qualified as rather "thin" (Grzelka and Wagner, 2019). However, the contribution of economic analysis can bring new interesting insights. For instance, the modelling of strategic interaction between different firms that compete for a limited space but do not fully (or not even partially) account for the negative effects of their actions appears to be an adequate framework to study the outcomes in terms of space debris generation under different market structures. This is the approach that we follow in this contribution. There are some characteristics of the so-called New Space Economy that we explicitly consider. The first one is the consideration of a growing number of agents competing in this market; while the satellite operation and services is not the most concentrated subsector of the space commercial activity, it is still far from being a competitive market (Giannopapa et al., 2018). The second one is the evolution through time of the mass of space objects and the coexistence of bigger objects with constellations of smaller ones (Diserens et al, 2020). The third one is the joint consideration of the direct effect of space debris (in terms of expected cost of collision) and the indirect effect (in terms of the limit to the capacity of orbits to host operating satellites).

First we present our theoretical model and the derived results. The predictions of the model are to be tested using the evidence derived from multiple datasources. We collect data on the estimated costs of different technologies that are currently under development. Using that information, simulations will be conducted.

1.2 Methods

We first present a theoretical framework to emphasize the importance of the increasing number of players in the satellite services market. The model provides an evaluation of the external costs imposed by each firm on the rest of the market in the absence of any intervention. These external costs depend on the market structure. We calibrate the model using values taken from the literature to highlight the importance of the different market structures.

We use data on space satellite activity to estimate the parameters of the model and the external effects. Then, we will test some hypothetical policy interventions that can help to reduce the new generation of mission related debris.

1.2.1 Model

Table 1 below summarizes our notation and provides the probabilities of the different collision events.

Table 1.1: The Main Variables

Variable	Name
π	Profit by period of one satellite
Π	Profit of satellite owner
C	Cost of one satellite
N	Number of active satellites
N_j	Number of active satellites of firm j
T	Satellite lifetime in years
p	Probability of destruction of a satellite due to collision
$(1-p)^N$	Probability that no satellite is destroyed
$p(1-p)^{N-1}$	Probability that exactly one satellite is destroyed
...	
$p^{N-1}(1-p)$	Probability that exactly N-1 satellites are destroyed
p^N	Probability that N satellites are destroyed

In this model, part of the cost of space debris is the expected cost of replacing the damaged spacecraft or satellite (direct effect). A second (indirect) effect of space debris is that it affects the optimal number of operating satellites. First, as a benchmark, we assume that all the satellite services are provided by a monopolist. Later on we analyze the more realistic case of several actors in the satellite industry.

When there is only one firm, its decision is to launch an optimal number of satellites N^*. This decision takes into account the effect on the probability of collision, which is increasing with the number of satellites in orbit. Once the optimal level N^* is determined, the firm will maintain it, even in the case of collision. This implies that when a satellite is destroyed, it will be replaced so that the number of operating satellites is always at the optimal level.

To simplify the analysis, we assume that the profits that a satellite can generate are a decreasing linear function of the number of them, that is:

$$\pi = a - bN \tag{1.1}$$

In other words, an increasing space activity makes each additional satellite less profitable since the more profitable activities are undertaken first. To simplify calculations, we assume that satellites have an infinite lifespan and can only be destroyed by collision.

In the case of a single provider of satellite services, the firm's expected profits may be written as:

$$\Pi = D\pi N - CN - DC\rho(N) \tag{1.2}$$

where D is $\frac{\delta}{1-\delta}$ and δ is the discount factor; π, N and C are defined in Table 1.1; $\rho(N)$ is the expected number of spacecraft that are damaged by collision each period and have to be replaced. C$\rho(N)$ represents the expected cost of replacement per period. In this setup $\rho(N)$ can be expressed as a function of the probability of collision p and the number of operating satellites N:

$$\rho(N) = \sum_{j=1}^{N} jp(N)^j(1-p(N))^{N-j}$$

Note that as N tends to infinity, then $p(N)$ tend to one and $1-p(N)$ tends to zero. Therefore, $\rho(N)$ tends to N. We assume that $\delta\pi < C$ in order to have negative profits from launching a satellite that almost surely will collide. Thus, the expected profits from satellite activity are:

$$\Pi(N) = \frac{\delta}{1-\delta}(a-bN)N - CN - \frac{\delta}{1-\delta}C\sum_{j=1}^{N} jp(N)^j(1-p(N))^{N-j} \tag{1.3}$$

The first term represents the revenues from satellite activity of N active satellites; the second term is the cost of construction and launching and the third is the expected cost of replacement in case of collision.

In the case of a single satellite services provider there are no external cost, since the impact on the probability of collision of the number of satellites launched is internalized. We analyze in the next section the case of multiple providers, where each firm does not fully internalize the effect of its activity on the probability of collision for other providers.

To obtain the optimal number of satellites for a single provider we maximize (1.3):

$$\frac{\partial \Pi}{\partial N} = \frac{\delta}{1-\delta}(a - 2bN - C\frac{d\rho(N)}{dN}) - C = 0 \tag{1.4}$$

The expression above implicitly characterizes the optimal number of satellites in the case of a single provider, N^*. An increase of N produces more expected space debris and consequently raises the probability of collision p as well as $\rho(N)$.

For a single provider, its decision to launch a new satellite depends on space debris, as it raises the probability of collision and therefore the expected number to be replaced and eventually the expected profits from satellite activity.

In our empirical application, we use previous studies to define several scenarios concerning the probability of collision as a function of satellite activity (Adilov et al 2015).

Competing providers of satellite services

After analyzing the case of a single provider, we consider a more competitive market in this section, an oligopoly. To simplify the exposition, assume we have only two providers A and B that choose simultaneously and independently the number of satellites to launch. N_A and N_B represent the number of active satellites of each of the two firms. The revenue per satellite will be as follows:

$$\pi = a - b(N_A + N_B) \tag{1.5}$$

We can write the profit of provider A as:

$$\Pi_A = \frac{\delta}{1-\delta}[a - b(N_A + N_B)]N_A - CN_A - \frac{\delta}{1-\delta}C\rho(N, N_A) \tag{1.6}$$

where $N = N_A + N_B$ and $\rho(N, N_A) = \sum_{j=1}^{N_A} j(p(N))^j(1-p(N))^{N_A-j}$. And for B:

$$\Pi_B = \frac{\delta}{1-\delta}(a - b(N_A + N_B)N_B - CN_B - \frac{\delta}{1-\delta}C\rho(N, N_B) \tag{1.7}$$

where $\rho(N, N_B) = \sum_{j=1}^{N_B} j(p(N))^j(1-p(N))^{N_B-j}$.

From the FOC we get:

$$\frac{\partial \Pi}{\partial N_A} = \frac{\delta}{1-\delta}(a - 2bN - C\frac{d\rho(N, N_A)}{dN_A}) - C = 0 \tag{1.8}$$

and

$$\frac{\partial \Pi}{\partial N_B} = \frac{\delta}{1-\delta}(a - 2bN - C\frac{d\rho(N, N_B)}{dN_B}) - C = 0 \tag{1.9}$$

Equations (1.8) and (1.9) characterize the optimal number of active satellites that would maximize the expected profits of the two providers A and B. Note that the number of N_A depends implicitly on N_B so the decision of firm A of how many satellites to launch depend on the number of satellites launched by firm B and viceversa (N_A^* is in function of N_B^*).

This strategic interaction between providers comes, first, from the market of satellite services and the fact that revenues from a satellite depend on the number of them providing similar services and, second, from the externality generated by space debris. The optimal number of satellites decreases with the probability of collision and that probability is affected by the decisions of other providers.
An important difference with the case of a single provider is that in this case the external effects are not fully internalized.

In our empirical application, we assume there are several providers and we consider only commercial satellites.

A competitive market for satellite services

As the number of satellite services providers increases, the market becomes more competitive. In this section, we analyze the case of firms that do not have a significant market power. Each provider is small compared to the market and may have a negligible impact on π, as well as on the probability of collision p.

The profit function in this case is:

$$\Pi_i = \frac{\delta}{1-\delta}\pi N_i - CN_i - \frac{\delta}{1-\delta}C\rho(p, N_i) \tag{1.10}$$

where $N = \sum N_i$ and $\rho(p, N_i) = \sum_{j=1}^{N_i} j(p)^j(1-p)^{N_i-j}$. In this market structure each firm considers π (revenue per satellite) fixed as well as the probability of collision p in $\rho(N, N_i)$, independent of its own decisions.

Thus, each firm decides N_i to maximize profits:

$$\frac{\delta}{1-\delta}\pi = C + \frac{\delta}{1-\delta}C\rho'(p, N_i) \tag{1.11}$$

where $\rho'(p, N_i)$ is the derivative of $\rho(p, N_i)$ with respect to N_i. The market equilibrium conditions that characterize the optimal N^* are:

$$a - bN = C[1 + \frac{\delta\rho'(p, N)}{1-\delta}] \tag{1.12}$$

$$p = p(N) \tag{1.13}$$

where $\rho'(p, N)$ is the derivative of $\rho(N) = \sum_{j=1}^{N} jp^j(1-p)^{N-j}$ with respect to N. The first equation is the condition that demand equals supply and the second requires that the fixed probability of collision considered by firms in their optimization problems is consistent with the equilibrium number of active satellites N.

Note that in this case firms do not internalize the impact of their decisions on space debris. The supply curve for satellite services is the marginal cost of the industry, the right hand side of equation (1.12), and in this expression the derivative $\rho'(p, N)$ considers p as fixed. The fact that each provider i considers the probability of collision p as fixed (independent of N_i) implies that there is not even a partial internalization.

Inefficiency and mitigation measures

In this section we first characterize the efficient solution and then propose measures to implement it. We consider a perfectly competitive market; its equilibrium number of satellites is given by equations (1.12) and (1.13) in the previous section.

The efficient solution corresponds to a level of N such that the social marginal cost is equal to the social marginal value:

$$a - bN = C[1 + \frac{\delta\rho'(N)}{1-\delta}] \tag{1.14}$$

where $\rho'(N)$ is the derivative of $\rho(N) = \sum_{j=1}^{N} jp(N)^j(1-p(N))^{N-j}$ with respect to N. In contrast with the equilibrium condition (1.12), here p is not a constant and the marginal social cost takes into account the impact on the probability of collision of new launches.

A fiscal policy could increase the firms' marginal cost up to the level of the social marginal cost, so that in equilibrium the number of satellites would be socially optimal. In particular a tax per satellite equal to

$$\tau = C\frac{\delta}{1-\delta}[\rho'(N) - \rho'(p, N)] \tag{1.15}$$

would implement the optimal solution (1.14).

In this and the previous sections we have emphasized the external effects imposed on other firms through the probability of collision and the need to replace the damaged aircraft. However, note that if the probability of collision is high enough the space economic activity may become unfeasible or unprofitable and the corresponding social surplus would be lost. In the next section we focus on the social surplus that is lost due to space debris.

1.2.2 Value of space activity

We compute the loss of total surplus due to space debris. We assume a competitive market. In equilibrium total surplus is:

$$\int_0^{N^*} (a - bN - C - C\frac{\delta\rho'(p, N)}{1-\delta})\, dN \tag{1.16}$$

We compare this surplus with the total surplus that would be generated in the absence of space debris and, therefore, a negligible probability of collision:

$$\int_0^{N^{**}} (a - bN - C)\, dN \tag{1.17}$$

Where N^{**} is the new equilibrium value (larger than N^*). Thus, the value of the economic activity prevented by space debris is:

$$\int_0^{N^{**}} (a - bN - C)\, dN - \int_0^{N^*} (a - bN - C - C\frac{\delta\rho'(p, N)}{1-\delta})\, dN \tag{1.18}$$

Note that this expression contains the loss of surplus due to the loss of space activity (the difference between N^{**} and N^{*}), as well as the increase of costs for the replacement of the aircraft due to collision.

To estimate the economic impact of space activity, previous empirical studies have based their valuation on four main indicators, job creation, GDP/GVA, government revenues and spillover effects. Table 1.2 provides measures of impact.
It is estimated that each 1 euro investment made generate around:

Table 1.2: Estimated returns on 1 euro of investment

GDP	Spillovers	Employment	Government revenues
1.9	1.9	2.3	N/A

Source: Euroconsult (2019)

Economic impact of space activity on employment

In our model space debris limits space activity to N^{*}, instead of $N^{*}*$. The value of the additional space activity translates also into lower employment.

Economic impact of space activity on GDP/GVA

In our model space debris limits space activity to N^{*}, instead of $N^{*}*$. The value of the additional space activity translates also into a lower GDP.

Spill-overs of space activity

Spillovers refer to impacts of space activity that are not captured by the GDP or employment and include other indicators such as technology development, innovation and data exploitation. The data generated is very valuable as it can be used by scientist, commercial users, development agencies, and policy makers. Note that the spillovers vary depending on the nature of satellites activities. In the case of telecommunication satellites the spillover effect is different from the Earth Observation (EO), the downstream revenues are generated not by the data collected but from the broadcasting and communication services, such as consumers access to internet by satellites, communication with mobiles, governments communications and so on.

Economic impact of space activity on government revenues

Taxes related to satellites production and launching are also part of economic impact, they can be direct government revenues through taxes on transactions, salaries and consumption. For the Taxes, it is estimated that the contributing countries will indirectly be recovering more than 60% of the overall cost of the programs.

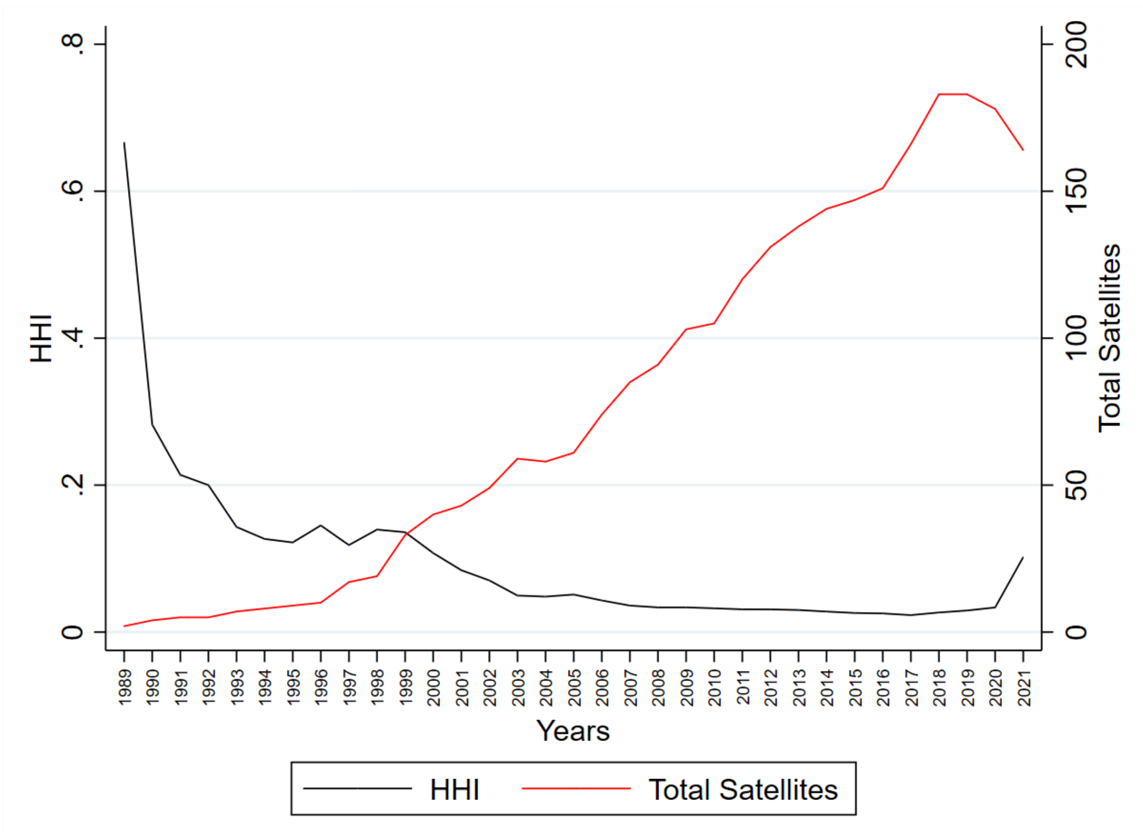
According to a Euroconsult Socio-economic impact assessment of selected ESA programs report, a generation of €8 billion of government revenues (taxes) is estimated over the full period of analysis (2007-2032) and in the economies of ESA 22 Member States, plus Canada and Slovenia

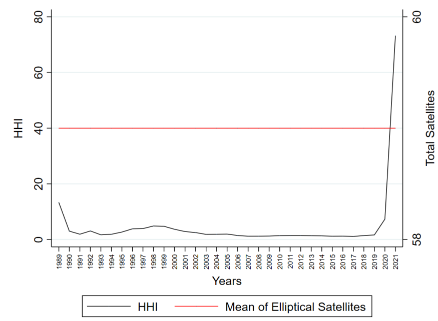
1.2.3 Calibration of the model

The below graph represents the evolution of the satellites by HHI Index (for Market concentration). The volume of satellites since the first spacecraft launch (Sputnik in 1957) escalated from around 1 satellites launch per year to up to 70–90 launches a year, an increasing number of launches injecting 30 or more small satellites into orbit at once (ESA). This higher launch cadence and the decrease of manufacturing cost in the past couple decades affected the concentration of the market, it is far more competitive with less entry barriers (a rise in the number of businesses, SMEs, start-ups and incubators) and thus the decline illustrated below:

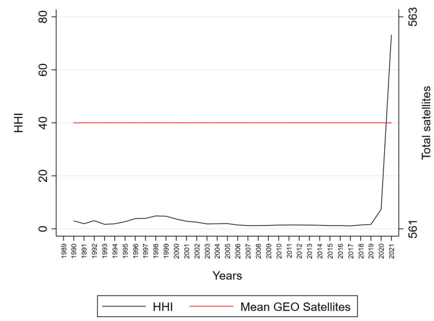
The concentration by orbit type represented by the following graphs, as illustrated in the graph the last couple years in all orbits we can see a higher concentration, this goes back to the decrease of launch rate across all orbits types.

Figure 1.1: Number of satellites and concentration over the years

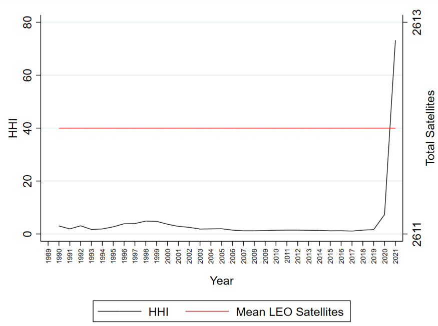




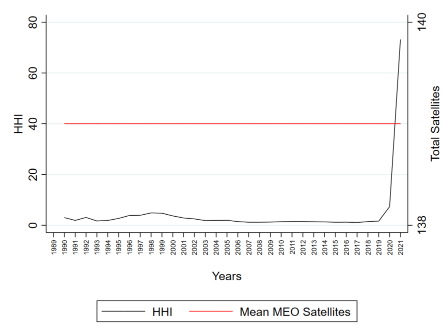
(a) Elliptical Orbit



(b) GEO Orbit



(c) LEO Orbit



(d) MEO Orbit

Figure 1.2: Concentration index by orbit type

1.3 Data and Empirical results

The Data represent general information regarding the satellites that have been launched in the past 40 years available from Space-track (US Air Force), European Space Agency and NASA. It includes more than 3300 satellite launched since 1974 and are described by 200 variables.

The table below represents the relevant variables and a brief description:

Table 1.3: Description of variables

Variable Label	Descritpion
Name of satellites	Name
Country of origin	Country
Users	The type of users of the satellite (Civil, Military..)
Purpose	Nature of activity (Surveillance, Communication)
Type of orbit	Polar, Equatorial or Elliptical
Class of orbit	Low, Medium or Geostationary
Date of launch	The date of launching
Expected lifetime	Lifespan of the satellite in years
Dry mass	The mass of the rocket at full ascent (Kg)
Launch mass	The mass of the launch vehicle upon takeoff (Kg)
Perigee	The point in the orbit at which the satellite is nearest to the earth
Apogee	The point at which the distance is greatest
Letters (AB, AC..)	Describe the sources of the launching information

1.3.1 Estimating the probability of collision

Probability of Collision is one of the most main metrics at present for collision avoidance measures, $p_c(N)$ incorporates different mathematical models which makes it much more rigorous than the other methods.

$$p_c(N) = \frac{1}{2\pi\sigma x\sigma y}\int_{-r}^{r}\int_{-\sqrt{r^2-x^2}}^{\sqrt{r^2-x^2}} e^{-1/2}[(\frac{x-xm}{\sigma x})^2 + (\frac{y-ym}{\sigma y})^2]\,dydx$$

The above equation represents the computational form of the probability based on Alfano and Oltrogge paper (2018), this model is very sensitive to inputs (Object size, shape and orientation) and therefore it is very crucial to determine the independent variables as they can give erroneous results.
This Probability assumptions are:

- Motion of the conjunction objects is fast enough (to be considered linear).
- Errors are zero-mean, Gaussian and uncorrelated.
- Covariance (size, shape, orientation) is assumed constant
- Objects are modeled as spheres.

In our model we will be focusing on estimating $p_c(N)$ as a function of volume (kg) and size, based on the same paper we have:

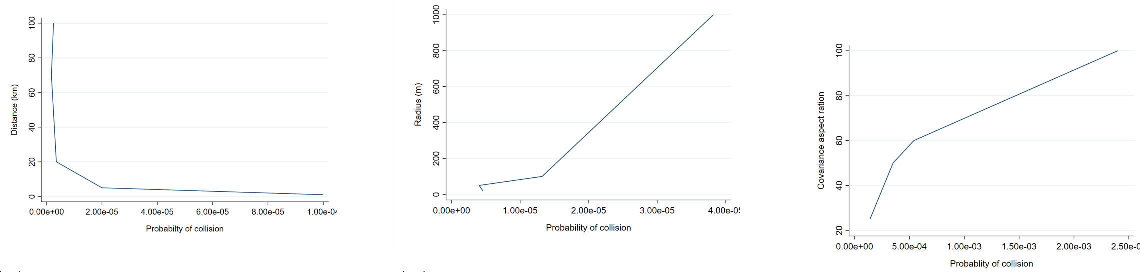
$$P_c max = (\frac{\alpha}{1+\alpha})(\frac{1}{1+\alpha})^1/\alpha$$

α includes the size of the object and it's represented by the following equation:

$$\alpha = \frac{r^2 AR}{d^2} \qquad \text{with} \quad AR > 1$$

The AR is the covariance aspect ratio (shape), d is the miss distance (the maximum distance at which the explosion of a missile head can be expected to damage a target, dictionary of aviation copyright 2005). The graphs below show the estimated probability of collision for different shapes and sizes and distances based on the Alfano et Oltrogge (2018) nomogram.

The distance graph illustrates how the least the distance between the objects the higher the probability of collision, note that d represents the miss distance in km, for the second graph to see the impact of the AR (shape) and the size (r) of the objects on the probability of collision we fixed the distance at 1 km.
With the distance ceteris paribus, we can conclude that larger the size and the sizeable the shape the more likely the objects to collide.



(a) Probability of collision by distance (km)

(b) Probability of collision by size (m)

(c) Probability by AR

Figure 1.3: Probability of Collision as a function of Distance, size and covariance aspect ratio

1.3.2 Estimating the cost of replacement of damaged satellites or aircraft

Based on the simulations and the test cases that were run by NASA using the Perfect option 5. the collision probability between a cataloged space object and a launch vehicle with a 200m radius is estimated around 1.93E-03 (newer computations estimate it around 1.79E-03). Once we have estimated $p(N)$, We then substitute it in $\rho(N)$.

$$\rho(N) = \sum_{j=1}^{N} jp(N)^j(1-p(N))^{N-j} = \frac{1}{-4p+4p^2+1}(1-p)^N - pp^N - \\ p^2(-p+1)^N + p^2p^N - Npp^N + 2Np^2p^N$$

Replacing $p(N)$ with it's estimated value:

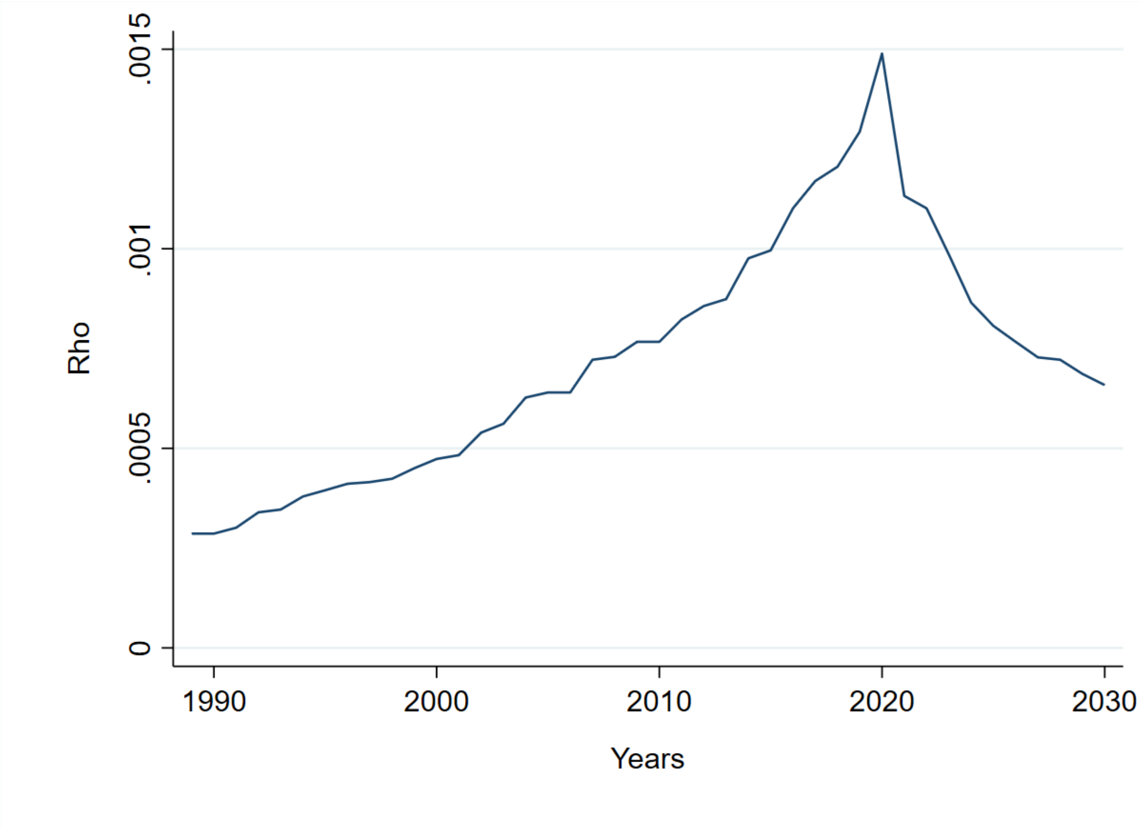
$$1.802 \times 10^{-3} \times 0.99^N - 1.802 \times 10^{-3} \times 0.0017^N - 1.796 \times 10^{-3} \times 0.0017^N N$$

and the estimated $p(N)$ and $\rho(N)$ in the equilibrium conditions 1.4, 1.8, 1.9, 1.10 and 1.11 to obtain the optimal N:

$$\frac{d\rho(N)}{dN} = \frac{1.802 \times 10^{-3} \times 0.99^N - 1.802 \times 10^{-3} \times 0.0017^N - 1.796 \times 10^{-3} \times 0.0017^N N}{dN}$$

The graph show the evolution of the cost of replacement by the number of satellites launched across the years, at the early years we see a steady increase of the cost of replacement due to the increase of satellites launched, the higher the number of

Figure 1.4: Evolution of cost of replacement $\rho(N)$ by number of satellites (N)



satellites the higher the probability of collision and thus the cost of replacement. on the contrast, the years after 2019 have seen a decrease in the number of launches comparing to the years before which explains the drop in the cost of replacement (less probability of collision).

1.3.3 Mitigation measures

Mitigation measures play an essential role to preserve the outer space environment and guarantee its sustainability since as demonstrated earlier, the debris present a menace to new launch missions and the functioning of previous spacecrafts and satellites, and to some extent a high risk to crew safety and also a hazard to earth in case of atmospheric re-entry.
The debris mitigation measures can be summed in two main categories: near term and long term. The short term involve the reduction of collisions and the generation of debris related to new missions (avoidance manoeuvres and passivation), the long term is based on de-orbitting and removing spacecrafts and launch vehicle that are

no longer of use from very populated and operational orbits and the compliance of guidelines. The united nations office for outer space affairs has developed a framework structure (guidelines) that should be followed in the early stages of planning, manufacturing, design and later on for the launching and the disposal. The guidelines can be summarized in:

- Limitation of the space activity (Spacecrafts and launch vehicles) in the LEO and GEO.
- Avoiding intentional destruction and minimizing post mission breakups (stored energy)
- Limiting the debris released and collision in orbit (separation mechanisms and deployment).

As of now The only used measures based on ESA's data are the collision manoeuvres and passivation. The collision manoeuvres vary depending on the orbit type of the spacecraft, for the LEO per instance the only possible and recommended disposal is the re-entry to earth atmosphere, while for other orbits the graveyarding technique is the most effective up to now manoeuvre under which the space craft have to re-orbit at an altitude no less than 300KM above the GEO ring to ensure that objects cannot collude nor interfere. The passivation technique is implemented at the early stages of the manufacturing (energy reservoirs), it consist of removing all form of energy sources to avert explosions while in orbital stage. Such energy can be residual propellants, fuel and the discharge of batteries.

Active Debris Removal

The active debris removal summarizes new concepts developed by space agencies to clean space at a rate of 5 to 10 objects per year some of these concepts are (Based on the International Interdisciplinary Space Debris Congress report, 2012) :

- Momentum exchange or electrodynamics (LEO only) tether
- Attaching a deboost motor
- a balloon (LEO only) or adding a device to the object to increase drag
- Deploying a reusable tug that grapples and moves
- Retrieval (return to earth, recycling in space) of the object

The main constraint when it comes to the ADR is that they should be cost effective. Some of these ADR are estimated to start by 2060 (ESA) but it would be 26% less effective than if used now.

Taxes

an Economic solution to the debris issue can be summarized in a tax schedule.

Few economist tried to model a taxation scheme for the outer space due to its particularity. Adilov et al (2015) found that perfect competition between firms results in a level of satellite launches, that surpasses the social optimum and investment in debris mitigation that is below the social optimum. The authors derived a two-part Pigouvian tax for that specific type of market context: The tax takes into consideration a debris creation parameter and it is applied per launch. The authors also suggest that the revenues can be used to finance new debris removal technologies.
On the other hand Macauley (2015) also prescribed a system of launch taxes focusing more on LEO's as they are more populated and have a higher volume of debris; she matches the taxes (at launch) with refunds to companies that apply end-of life disposal measures to their satellites and spacecrafts. Her approach includes rebated taxes to satellite producers for incorporating certain ex ante debris mitigation technologies such as graveyarding, orbital manoeuvring and shielding and these measures can also yield some spillover benefits.
Based on our model and the perfect competition setup we consider a tax per satellites (equation 1.15), equal to:

$$\tau = C\frac{\delta}{1-\delta}[\rho'(N) - \rho'(p,N)]$$

1.4 Conclusion

Space by definition is considered a public good, its market opportunities are related to the exploitation and the exploration of outer space which can be represented by data gathered, communication and navigation's (each satellite provide a service). In contrast the market failure arise from the externalities related to the use of the public good (common property) such as Debris, resources allocations, the large fixed cost related to space activity and manufacturing, under-investment situation and finally the limit spill over effect that only few countries benefit from.

The Space debris problem is threatening the sustainability of space and damaging the environment, the availability of orbital sloth and bandwidths coverage has became less and less attainable due to the exponential increase of launching rates, collisions between debris or extant satellites creates additional debris. In the limiting case, collusion cascading could reduce the realized value of certain earth orbits to zero. Many scientist and space agencies are estimating more debris generation and ultimately a non accessible outer space due to the higher probability of collision that increases with every new launch mission.

The aim of this paper is to study the impact of increasing space activity (under different market structures: Monopoly, oligopoly and perfect competition) by valuating the debris in outer space and its cost and then model a policy intervention that can help reduce the new generation of mission related debris. We illustrated an approach to quantify the cost of debris based of the firm profits and the probability of collision under the three market structures. Space debris is an externality generated by expended launch vehicles and damaged satellites our model gave us in the case of a single satellite services provider no external cost since the impact on the probability of collision of the number of satellites launched is internalized, in contrast for the perfect competition and oligopoly the firms respectively do not internalize the impact of their decisions on space debris or they are not fully internalized. The internalization of externalities related to space activity (or debris) can be represented by an enforced liability (Todd sandler, Global collective action), the damages caused or the debris based on the "outer space treaty" is assigned (the liability) to the nation or organisation responsible for the launching and operating. the more a nation has large objects in orbit the less likely to internalize.

The previous debris mitigation measures implemented had a slight significance on the rate of debris generation and removal, the particularity of the issue goes back the fact that only guidelines in the design, manufacturing and launching needs to be followed but the volume of debris from previous space activities needs to cleaned. we argued that the more suitable economical approach would be a taxation system (Pigouvian) of launch taxes (ex ante) that is expected to reduce debris per satellite launched. This fiscal policy could increase the firms' marginal cost up to the level of the social marginal cost, so that in equilibrium the number of satellites would be socially optimal.

Bibliography

Muller C. Rozanova O. Urdanoz M. (2017). Economic valuation of debris removal. In 68th International Astronautical Congress

Adilov N, Alexander PJ, Cunningham BM (2015) An economic analysis of earth orbit pollution. Environ Resour Econ 60(1):81–98

Adilov, Alexander and Cunningham (2020). "The economics of orbital debris generation, accumulation, mitigation, and remediation".Journal of Space Safety Engineering7(3) 10.1016/j.jsse.2020.07.016

Diserens, S., Lewis, H. G., and Fliege, J. (2020). NewSpace and its implications for space debris models. Journal of Space Safety Engineering, 7(4), 502-509.

Giannopapa, C., Adriaensen, M., Antoni, N., and Schrogl, K. (2018). "Elements of ESA's Policy on Space and Security". Acta Astronautica, 147, 346–349.

Grzelka, Z., and Wagner, J. (2019). Managing satellite debris in low-earth orbit: Incentivizing ex ante satellite quality and ex post take-back programs. Environmental and Resource Economics, 74(1), 319-336.

Macauley MK (2015) The economics of space debris: estimating the costs and benefits of debris mitigation. Acta Astronaut 115:160–164

Patera P, (2001) General Method for Calculating Satellite Collision Probability. Journal of guidance, Control, and dynamics Volume 24, Issue 4.

Rao, A., Burgess, M. G., and Kaffine, D. (2020). Orbital-use fees could more than quadruple the value of the space industry. Proceedings of the National Academy of Sciences, 117(23), 12756-12762.

Rouillon, S. (2020). A Physico-Economic Model of Low Earth Orbit Management. Environmental and Resource Economics, 77(4), 695-723.

Undseth, M., Jolly, C., and Olivari, M. (2020). Space sustainability: The economics of space debris in perspective. OECD, Paris.

Young Sook Eom, Jong Ho Hong, (2013) Measuring the economic benefits of an environmental monitoring satellite project: The value of information approach. Space Policy, Volume 29, Issue 3, Pages 203-209.

PWC, (2019) Socio-economic impact assessments and accompanying foresight study of selected ESA Earth Observation activities, Executive summary.

EUROCONSULT for the European space agency, (2019) Socio-Economic impact Assessment of ESA's activities on secure sitcom for safety and security.

EUROCONSULT for the European Space agency in partnership with technopolis and oxford economic; (2019), Socio-economic impact assessment of selected ESA telecommunication Partnership projects.

Salvatore Alfano, Daniel Oltrogge (2018) Probability of Collision: Valuation, variability, visualization, and validity. Acta Astronautica, Volume 148, Pages 301-316.

Committee on the Peaceful Uses of Outer Space Scientific and Technical Subcommittee Forty-ninth session Vienna, 6-17 February 2012 "Item 14 of the draft provisional agenda* Long-term sustainability of outer space activities"

Adilov N, Alexander PJ, Cunningham BM (2018) An economic "Kessler Syndrome": a dynamic model of earth orbit debris. Econ Lett 166:79–82