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To Launch, or not to Launch? A Model of Space Debris and Satellite Operator Decision Making

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Abstract

The space industry is a critical enabler of high productivity jobs, innovation, public services, and defence capabilities that have transformed life on Earth. However, the current way in which we launch satellite assets is unsustainable due to the growing problem of space debris. If left unchecked, the expected loss could accelerate as collision probabilities increase exponentially under a 'Kessler Effect'. This growing problem stems from space being a common, shared resource, with economic agents not internalising the negative social costs associated with increasing orbital debris. This has led to a growing public debate on potential strategies to mitigate this issue and promote sustainability in space. In this paper, we examine the impacts of debris mitigation policies on the incentives of private satellite operators to engage in launch activities. We develop a dynamic economic model that considers the choice of multiple operators on whether to develop and launch a satellite. This choice is dependent on the risk of collision, which is modelled as a function of the other operators' decision to launch. Using this theoretical framework, we discuss various factors for policy makers to consider when deciding how to implement debris mitigation policies.

Keywords: Space Debris, Kessler Effect, Collision Risk, Incentives, Sustainability, Tragedy of the Commons

1. Introduction

The space industry has generated products and services which have led to significant advancements in science, technology, and the quality of life on Earth. While government-backed programmes such as Landsat, Copernicus, the Global Positioning System (GPS), and Galileo remain critical to society, a combination of low-cost launch, cheaper manufacturing techniques, commercial-off-the-shelf (COTS) components, new design philosophies, and private capital have encouraged a huge increase in private sector participation in space [1].

These private participants are driven by the promise of high returns in what is considered an underexploited frontier market at a critical inflection point: growing private interests are transforming space from a government-led endeavour [2] with few participants and a small number of launches to one with diverse participants and a large and growing number of launch activities. Operators of satellite assets – whether communications (Satcom), Position, Navigation, and Timing (PNT), Earth Observation (EO), 'In-Space' or others – each make a 'private' decision to launch based on an assessment of the private costs and private benefits of this activity. The difference between the discounted stream of revenues earned from the satellite, and the discounted cost of the satellite, ground segment, launch service, insurance, associated rights, and the ongoing operating costs, will determine whether the operator will invest or not. In making this assessment, the operator will also adjust benefit estimates for assumptions of technical and market risk which may cause the return to be lower in some scenarios. One example is launch failure or the risk of in-space collision which may degrade satellite performance and reduce satellite lifetimes.

The 'private' decision to launch accounts for the operator's perceptions of collision risk implicitly, but it does not account for the broader implications. These include potential collateral collision risk and the subsequent impact of service disruption borne by other satellite operators and end users, as well as the long-term impact of space debris risk on future operations beyond the lifetime of the asset in question. These wider costs sit outside the private operator's decision criteria and suggest a mismatch between launch decisions that are optimal for the operator and launch decisions that are optimal for society as a whole.

In this paper, we use a model to investigate the impact of debris mitigation policies on the incentives of private satellite operators to launch. We find that debris mitigation policies change the composition of satellite operators that remain 'active' in the industry, as those with the smallest margins (the difference between operational profit and the fixed cost of delivering a satellite to orbit) are more likely to leave the market following the imposition of these policies. We find that the cost of the policy lowers the threshold collision probability at which no operator chooses to launch in the long run. Additionally, we find that the overall welfare of the debris mitigation policy will be determined by the relative change in the parameters characterising the fixed cost of delivering a satellite to orbit, and the proportion of satellites that are deorbited.

The paper proceeds in the following way. Section 2 reviews the relevant literature and explains the motivation of the paper. Section 3 constructs a model characterising the decision of a private satellite operator to launch in a given period of time. Section 4 presents the simulations of the model. Section 5 discusses the implications of the main findings. Section 6 reviews the limitations and possible extensions of the model. Section 7 concludes.

2. Review of literature and motivation

2.1 The importance of the space environment

Space assets underpin numerous commercial and public sector capabilities, including Critical National Infrastructure (CNI) such as electricity networks, transport, and emergency services [3]. The criticality of space also extends to defence and national security. For example, the UK's Ministry of Defence (MOD) recognises space as the 'fifth operational domain' and one which is fundamental to the potency of military power [4].

The space industry is also a significant industry in its own right. Several estimates of the global space economy suggest a $400bn market size in 2022 [5,6,7], with an economy's overall reliance on space many times greater than the direct contribution of the space industry to economic output [8]. This reliance on space assets and vulnerability to loss of such assets, such as GNSS [3], has developed over decades and is based on assumed availability, security, and continuity of satellite signals and services.

At the same time, technological advances and a new influx of private capital are encouraging the growth of an 'In-space' economy and a huge increase in the assets built and activities undertaken in space. This new ecosystem includes a range of services to move, refuel or image existing assets, assemble new ones, and manufacture materials within the space environment. Together, these capabilities promise an improvement in the costs of space missions, new commercial opportunities, and growth of the global space industry [9]. However, the current way in which we launch satellite assets places this future at risk. This is due to the growing problem of space debris.

2.2 The growing problem of space debris

Space debris, also known as 'space junk', refers to the collection of defunct satellites, spent rocket stages, and other discarded fragments orbiting the Earth. This debris poses a significant problem for continued space exploration and satellite operations due to the risk of collisions which can degrade or destroy satellite assets and undermine substantial capital investment. Even a relatively small-scale collision event could produce large debris clouds, which then cause a cascading cycle of increased debris and an increased number of collisions, known as the "Kessler effect" [10]. This exponential increase in collision risk will eventually lead to a state where large swathes of the orbital environment are unusable.

Numerous studies have been conducted highlighting this growing risk [11,12,13]. For example, analysis by NASA (Figure 1) indicates that orbital debris has grown in both number and total mass since the beginning of the space age, with significant jumps due to major debris-generating events such as the Chinese ASAT test (2007), the Iridium-Cosmos collision (2009), and the Russian ASAT test (2021) [14].

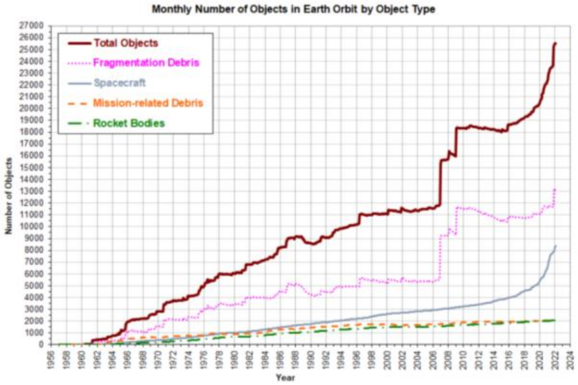

Figure 1. Monthly number of objects in Earth orbit by type [14]

Figure 2 illustrates that the space debris problem is mainly concentrated in Low-Earth Orbit (LEO), especially between 600km and 1000km [13]. This trend reflects the increasing use of LEO for 'mega-constellations' of hundreds or thousands of satellites to provide global broadband (e.g., SpaceX, OneWeb, Amazon Kuiper) or support novel Earth Observation missions.

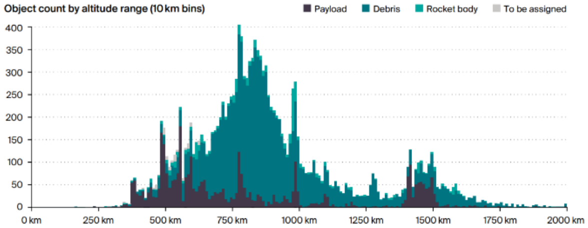

Figure 2. Publicly available catalogue of space objects tracked by US SSN [13]

Measurement of the precise volume of debris and the scale of the problem are limited by the capabilities of ground and space-based sensors [15]. Estimation therefore relies on statistical modelling techniques. For example, the European Space Agency's (ESA) Meteoroid and Space Terrestrial Environment Reference "MASTER" models debris risk and the likely evolution of collision probabilities over time [16]. As of September

2024, the model estimates 10,200 active satellites in orbit, 40,500 objects larger than 10cm, and 130 million objects smaller than 1cm orbiting the Earth [17]. Various models and simulations have been used to quantify and predict collision hazards in LEO [18,19]. Other studies have complemented this approach using simulation and modelling to investigate the long-term dynamics of space debris, more specifically, investigating the interactions between the deployment of large constellations and the impact on collision risk and debris generation [20,21]. Additionally, combinations of statistical analysis with simulations have been used to evaluate collision probabilities involving mega-constellations to offer detailed insights into the evolution of collision risk [22,23,24] or investigated probabilistic risk models to assess the long-term impact of large constellations on space sustainability [25].

Beyond LEO, other studies have presented space debris modelling that covers the entire orbital range from LEO to GEO, highlighting the difference between orbital planes, utilising a hybrid approach with both physical simulations of debris and statistical analysis of distributions of debris [26]. Other methodologies include the use of Machine Learning techniques to predict the evolution of space debris, particularly in densely populated orbital regions [27,28].

These studies suggest that the continued deployment of satellites in significant numbers – to expand existing constellations, create new ones, and replace old ones – in the next decade, will contribute to orbital congestion, the risk of catastrophic collision, and the loss of satellite services which underpin economic, security, and public sector capabilities.

While there are several studies that have modelled the number of debris, long-term behaviour of space debris, and orbital collision probabilities, few have attempted to combine collision probabilities with satellite asset values to assess the total value at risk. Previous analysis by London Economics estimates cumulative ‘value at risk’ (i.e., the sum of satellite asset values and their collision probabilities) in 2020 of $4.6bn in LEO and $46bn in GEO [11]. However, the average collision probabilities in 2020 are relatively higher in LEO (~1 in 320/year vs ~1 in 50,000/year), so the annual expected loss, or the product of value at risk, and collision probability, is significantly higher in LEO at $23m compared to $1.2m in GEO. The increase in asset volumes and values in LEO and the increasingly congested orbital environment, contribute to a significant increase in the annual expected loss in LEO over the next 15+ years. The study demonstrated the average expected loss in a given year, but actual losses could be significantly higher and could even multiply exponentially under a Kessler Effect. The estimates of asset values and collision probabilities in the study were estimated in 2019/20 before the acceleration in launch rates and the 2021 Russian anti-satellite test observed since then [14]. The collision probabilities and value at risk estimated in this 2020 study, particularly in LEO, should therefore be considered conservative.

2.3 Space as a ‘commons’

This growing problem of space debris can be summarised as a classic ‘Tragedy of the Commons’ problem. This idea is associated most closely with Garret Hardin who theorised in his 1968 article that rational behaviour from economic agents who have access to a shared resource, the ‘commons’, act in such a way as to deplete the resource [29].

The evolution of the space ecosystem, from a domain primarily controlled by government to one increasingly dominated by the private sector [30,31] has fostered the notion of space as a ‘commons’ [32] – a shared resource that has few regulations to access, leading to incentives to exploit it without responsibility or accountability. Private companies may not have the same incentives as governments and prioritise short-term profits over long-term space sustainability.

2.4 Addressing the problem

The problem of space debris has led to increasing public debate on potential strategies to mitigate this issue and promote sustainability in space. Simultaneously, it has driven increased research and development for technological solutions.

Space Situational Awareness (SSA) represents one solution to manage the problem through greater domain awareness. If operators have better visibility of the space environment, they can undertake manoeuvres to avoid collisions with observable debris, albeit at the cost of propellant and therefore reduced asset lifetimes. Operators can also adapt to the riskier environment by hardening satellites against collisions [33], but this increases satellite mass, volume, and therefore launch costs. Both solutions represent management strategies to reduce the potential impact of debris but do not directly remedy it.

However, several remediation technologies have been proposed to solve the problem. These can be broadly divided into two groups:

Debris removal (removing objects from orbit):

- End-of-Life removal (EOL): Removal of prepared space objects with pre-fitted mechanisms for removal;
- Active Debris Removal (ADR): Removal of unprepared space objects (that may or may not be attitude controlled) through de-orbiting and re-entry into the Earth’s atmosphere;
- Physical sweeper: Large shields inserted into orbit to reduce the populations of small nontrackable debris through direct contact, by capturing, retarding, or breaking up the debris.

Collision avoidance (nudging debris out of the way):

- Ground/space lasers: Laser moves the debris to avoid a collision if the debris will have a close approach or is expected to collide with another object;
- Rocket nudges: Sounding rocket moves the debris to avoid a collision if the debris will have a close approach or is expected to collide with another object.

Interventions such as ADR and EOL seek to address the need for a more sustainable space environment by removing 'space junk' and reducing the collision risk to active satellites on which owners of assets and downstream users of space data depend. Mitigations like this may impose a cost on operators so this raises the question of what the impacts of debris mitigation policies are on satellite operators' incentives to launch, and on economic outcomes in general.

Within the literature, there are two studies that are closely related to what this paper tries to achieve. Macauley (2015) studies the economic impacts of various debris mitigation policies and concludes that a tax levied upon launch which is then rebated upon evidence of compliance with the mitigation action is the most cost-effective [34]. In this study, we take an intervention agnostic approach to assessing the impact of debris mitigation on welfare in our model.

Klima et al. (2016) analyse space debris removal from a strategic, game theoretical perspective. They demonstrate that the benefit/cost ratio of a debris removal mission plays a significant role in influencing the behaviour of various agents involved, analysing a one-shot game where space agencies decide whether to deorbit satellites. The study finds that at higher benefit/cost ratios, where the benefits of debris removal significantly outweigh the costs, agents are more likely to invest in debris removal efforts. However, at lower benefit/cost ratios where the costs outweigh the benefits, agents may be less inclined to participate in debris removal. [35]. In this paper, we take a more dynamic approach, analysing satellite operator launch decisions over multiple periods rather than as a one-shot game. This allows us to investigate long-term impacts of launch activities on collision probabilities, estimated payoffs, and therefore long-term operator launch decisions with and without debris mitigation policies. Additionally, we analyse the impacts of debris mitigation strategies that are levied upon all satellite operators, rather than characterising the adoption of these strategies as a private decision of various space agencies. This allows us to analyse how the incentives of private satellite operators are impacted by international legislation and global restrictions on debris that encourage operators to adopt mitigation options which to our knowledge are under-researched elements of the literature.

3. Theory and calculation

In this section, we construct an economic model that characterises the decision faced by private satellite operators to launch a satellite in a particular time period. Satellite operators balance the expected operational profit – a product of operational profit (operating revenues minus operating costs) and the risk of collision – and the fixed cost of delivering a satellite to orbit (henceforth, 'fixed cost').

3.1 Set-up of the model

There are N operators deciding whether to launch identical satellites in each time period. For simplicity, each satellite is assumed to launch in the same orbit and is therefore identical to others. Each time period is equal in length to the operational lifetime of the satellite, and an operator i can decide in each time period t whether to launch a satellite ($X_{it} = 1$) or not ($X_{it} = 0$).

If an operator chooses to launch a satellite, it incurs a fixed cost C, which is constant across operators and across time, and is incurred irrespective of whether the satellite experiences an in-orbit collision or not. If the satellite does not experience an in-orbit collision after launching, the operator receives an operational profit of π_i, which is drawn from a uniform distribution between 0 and 1, and is constant across time. Since the fixed cost C is identical across operators, variation in π_i across operators can be interpreted as variation in the operational profit relative to the fixed cost.

We model the probability of an in-orbit collision as a non-linear function of the number of satellites that are currently in orbit in a given time period t, S_t. The number of satellites in orbit is dependent on the launches up to and including that time period.

We assume that a fixed proportion of satellites launched, θ, decay naturally in their orbit in the same time period as their launch. This assumption is adopted as it corresponds to a further simplifying assumption that satellites are randomly distributed in their orbit height within Low Earth Orbit. We assume a certain proportion of this distribution, θ, are at a sufficiently low orbit to deorbit naturally within the time period. The remaining proportion are at a sufficiently high orbital height such that they do not deorbit within the study period.

Further, we assume for simplicity that the orbits are identical in their characteristics aside from their height, implying that a satellite will extract the same operational profit π_i regardless of the height it operates at. We also assume that for a given θ, operators cannot influence the probability of a given satellite deorbiting naturally.

The total number of satellites that are in orbit at a particular time period t is defined in equation (1). The total number of satellites in orbit in the previous time period in addition to a proportion $1-\theta$ of satellites launched in time period t, where X_t is the total number of satellites launched ($X_t = \sum_{j=1}^{N} X_{jt}$):

$$S_t = (1-\theta)X_t + S_{t-1}. \tag{1}$$

The total number of satellites in orbit in time period t can be expressed in terms of the total number of launches across all operators up to, and including, time period t.

$$S_t = (1-\theta)\left[\sum_{j=1}^{N}\sum_{q=0}^{t}\left(X_{jq}\right)\right] \tag{2}$$

The probability of an in-orbit collision (the collision probability, R_t) is modelled in equation (3).

$$R_t = a[S_t]^b \tag{3}$$

Parameters a and b are constants. b is assumed to be greater than one, so that marginal collision probability is increasing in S_t, reflecting the escalating risk associated with more satellites in orbit, and a and b are assumed to be sufficiently small, such that the collision probability R_t is not greater than one for any time period.

The payoff function for an operator i at time period t is presented in equation (4). An individual operator bases their decision in time period t on the expected payoff accounting for the observed collision probability in the previous time period (R_{t-1}), as we assume that the operator does not know if other operators are launching in time period t or not, trading off between the expected profit from launching a satellite and the fixed cost:

$$U_{it} = X_{it}[\pi_i[1-R_{t-1}] - C]. \tag{4}$$

3.2 Deriving the decision rule

Equation (5) gives the discounted sum of payoffs over all time periods for operator i, where the operator discounts the payoff from each subsequent time period with a factor β between 0 and 1.

$$U_i = \sum_{t=0}^{\infty}\beta^t(U_{it}) \tag{5}$$

The increase in payoff associated with launching ($X_{it}=1$) for $t>0$ is

$$\frac{dU_i}{dX_{it}} = \beta^t[\pi_i(1-R_{t-1}) - C] - \sum_{q=t+1}^{\infty}\pi_i\left[\beta^q X_{iq}\left(R_t'(X_{it})\right)\right]. \tag{6}$$

The first term can be interpreted as the contemporaneous impact on utility of launching in time period t, with the second term being the impact of launch in time period t on the utility in future periods through increased collision probability.

In addition to other assumptions, a and b are assumed to be sufficiently small such that the second term is negligible relative to the first, and so that the second term (where a and b are arguments of the collision probability function R) is negligible enough for the operator to not consider.

$$\sum_{q=t+1}^{\infty}\pi_i\left[\beta^q X_{iq}\left(R_t'(X_{it})\right)\right] \approx 0 \tag{7}$$

This assumption can be interpreted as follows: the impact an operator has on their future collision risk by their current decision to launch is negligible in comparison to the impact on their expected payoff in the current time period. The operator therefore focuses solely on the impact of their launch on the expected payoff in the time period of the launch.

Hence, the increase in payoff associated with launching can be simplified to

$$\frac{dU_i}{dX_{it}} \approx \beta^t[\pi_i(1-R_{t-1}) - C]. \tag{8}$$

Operators will only decide to launch if launching a satellite weakly increases their expected payoff, hence, the decision rule is

$$\frac{dU_i}{dX_{it}} \geq 0. \tag{9}$$

Which is equivalent to

$$\pi_i(1-R_{t-1}) \geq C, \tag{10}$$

where inequality (10) states that an operator will launch if the expected profit is greater than, or equal to, the fixed cost.

3.3 Launch, satellite, and collision probability dynamics

From (10), we can derive the proportion of operators that decide to launch in a given time period. Inequality (11) presents the condition for an operator to launch in time period t.

$$\pi_i \geq \frac{C}{1-R_{t-1}} \tag{11}$$

Given that π_i is distributed uniformly between zero and one, the proportion of operators (l_t) that decide to launch in period t is stated in (12).

$$l_t = 1 - \frac{C}{1-R_{t-1}} \tag{12}$$

The number of launches in period t is

$$X_t = \sum_{i=1}^{N} X_{it} = N\left(1 - \frac{C}{1 - R_{t-1}}\right). \qquad (13)$$

Using the initial condition $X_0 = 0$, X_t, S_t, and R_t can be expressed in terms of the sum of launches in previous time periods

$$X_t = N\left(1 - \frac{C}{1 - a\left((1-\theta)\sum_{q=0}^{t-1} X_q\right)^b}\right). \qquad (14)$$

X_t is increasing in θ, stating that an increase in the proportion of satellites that are deorbited, increases the number of satellites launched in period t.

X_t is decreasing in a, b, X_q, and C, suggesting that an increase in the probability of collision in $t-1$, or an increase in the fixed cost, will decrease the number of launches in period t.

Equations (15) and (16) express S_t and R_t, respectively, in terms of previous launches:

$$S_t = (1-\theta)\sum_{q=0}^{t} X_q\,, \qquad (15)$$

$$R_t = a\left((1-\theta)\sum_{q=0}^{t} X_q\right)^b. \qquad (16)$$

S_t is a decreasing function in θ, and increasing in X_q. R_t is increasing in a, b, X_q, and decreasing in θ.

3.4 Simulation

Using equations (14), (15), and (16), we can simulate the impacts of policy interventions which alter the values of certain variables. Figure 3 depicts how values are calculated over time in the simulation.

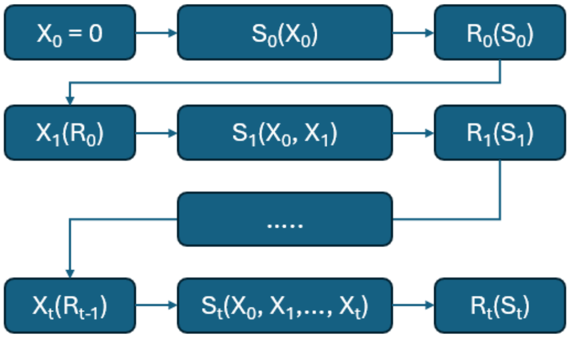

Figure 3. Model simulation flow-chart

4. Results

4.1 Simulation panels

Figure 4 depicts the various outputs of the simulation. Panel A describes the total number launches in each time period, using equation (14). Panel B considers the total number of satellites in orbit at each time period, utilising equation (15). Panel C plots the collision probability over time which is calculated using equation (16). Panel D charts the total expected payoff across operators at each time period, as shown in equation (17).

$$U_t = \sum_{i=0}^{N} \beta^t (U_{it}) \qquad (17)$$

Within each panel, there are three series that are presented. The grey line indicates the results from the baseline simulation. The green line shows the results from increasing the number of satellites that deorbit (θ), and the blue line shows the impact of increasing the fixed cost (C). In the baseline simulation (in grey), launches (Panel A) and total expected payoffs (Panel D) decrease over time towards zero. Panel B and C show satellites in orbit and collision probability increasing over time towards a long-term equilibrium where $X^* = 0$.

The long-term equilibrium for panels B and C can be characterised in equations (18) and (19) respectively.

$$S^* = \left(\frac{1-C}{a}\right)^{\frac{1}{b}} \qquad (18)$$

$$R^* = 1 - C \qquad (19)$$

Equation (18) shows that the long-term equilibrium in Panel B is determined by $a, b,$ and C. For Panel C, the long-term equilibrium is solely determined by C.

4.2 Changing the proportion of deorbited satellites (θ)

Using the simulation we can describe, for a given set of values, the impact of a change in θ from θ_{low} to θ_{high}.

In Panel A, we see an increase in θ leads to an increase in the number of launches for all time periods greater than one, relative to the baseline model, but the number of launches also decreases towards zero over time. Panel B shows that increasing θ has no impact on the number of satellites in orbit in the long-term equilibrium, but increases the time taken to reach that long-term equilibrium.

The same dynamics are demonstrated in Panel C for collision probability. Panel D demonstrates the same dynamics as Panel A, where total expected payoff is greater (for all time periods) compared to the base simulation.

A higher value of θ reduces the impact of launches on the number of satellites in orbit, and therefore on collision probability. This has subsequent impacts on the number of launches, and total expected payoff in each time period.

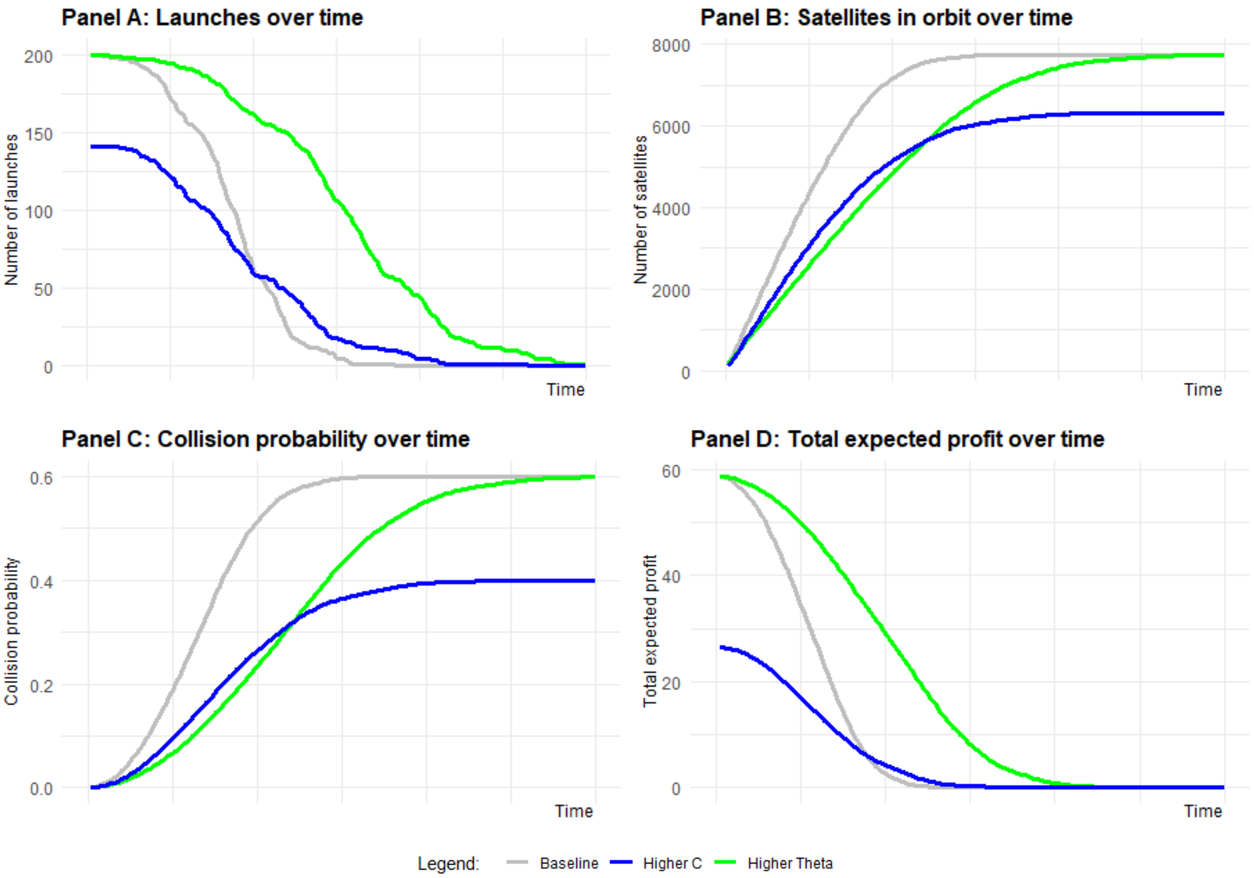

Figure 4. Model simulation

Note: The parameters used are as follows: $t = 200$, $N = 300$, $\beta = 0.95$, $\theta_{low} = 0.1$, $\theta_{high} = 0.5$, $C_{low} = 0.4$, $C_{high} = 0.6$, $a = 1x10^{-8}$, $b = 2$. *These simulations are for illustrative purposes only.*

4.3 Changing the fixed cost of delivering a satellite to orbit (C)

Panel A shows an increase in the fixed cost initially reduces the number of launches in earlier time periods. In later time periods, launches will be higher relative to the base model driven by a relatively lower collision probability that is caused by fewer launches in earlier time periods.

Panel B indicates that increasing cost will result in a lower total number of satellites remaining in orbit in the long term equilibrium. Similar dynamics are observed in Panel C. This can be explained by considering equations (18) and (19), where an increase in C, reduces the long term equilibrium for both the number of satellites in orbit (S^*), and the collision probability (R^*). Panel D shows similar dynamics to Panel A.

5. Discussion

Recent discussions regarding the issue of space debris have mainly centred around the various mitigation policies to address the problem. In the model presented in this paper, we characterise these policies with a combination of a higher fixed cost of delivering a satellite into orbit (C) and a higher proportion of satellites that are deorbited (θ).

Firstly, the implementation of the mitigation policy will change the composition of the private operators that decide to launch in each time period. Operators that initially have a relatively small margin – the difference between their operational profit (π_i) and the fixed cost (C) – are more likely to decide not to launch in periods following the imposition of the debris mitigation policy. This implies that the types of operators left in the space industry following the imposition of the debris mitigation policy will be different and that the types of activities that they undertake may also differ. This could have important implications for future policy interventions as the characteristics of the operators left operating in the space industry are now fundamentally different from before. It also means that certain activities which, while socially beneficial, may no longer be undertaken if they are associated with lower commercial margins.

Secondly, the long-term equilibrium of satellites in orbit will be impacted following the implementation of debris mitigation policies. Equations (18) and (19) show that the long-term equilibria for collision risk and satellites in orbit (when launches within a given time period is equal to zero), are both functions of the fixed cost rather than the deorbit proportion (θ). The cost parameter determines the number of satellites that can exist in orbit, whereas the deorbit proportion affects the speed at which that limit is reached. The increase in the deorbit proportion also has the affect of increasing launches in each time period, partly offsetting the direct effect of a reduction in collision probabilities. This implies that regardless of the proportion of satellites that deorbit in each period, if the cost levied on private operators is high, operators will stop launching at much lower collision probabilities than in the absence of the policy intervention. Policy makers should therefore consider the trade-off between increasing the amount of debris that is deorbited with the cost of the policy that is levied on private operators.

Thirdly, the overall operator welfare (proxied by the total expected profit) of the debris mitigation policy will depend on the relative difference between the fixed cost and the deorbit proportion. This is important for policy makers to consider, since if the cost levied on private operators is too high relative to the reduction in collision risk (through a higher θ), then the policy will end up leaving operators worse off than in the absence of the policy.

Additionally, while debris below 650km can naturally deorbit within 25 years due to atmospheric drag, debris removal is the only mechanism to stabilise the volume of debris at higher orbit heights [12]. If we consider both ADR and EOL, these technologies are in development and still require significant investment to mature into commercial services at scale. Likewise, current debris removal concepts assume limited utilisation and/or rely on the development of a broader refuelling infrastructure to lower costs, hence, unit costs for a single mission are likely to remain high as a proportion of total satellite costs, at least until volume and further development is achieved. Alternative removal strategies, such as the retention of reserve propellant and/or redundant propulsion systems add to manufacturing and launch costs (given higher launch mass and volumes). This implies that mitigation policies at higher orbits will involve a relatively higher increase in the fixed cost. As such, satellites in various orbits may, in practice, be affected differently by debris mitigation policies, although we make a simplifying assumption in the model that the characteristics of orbits at different orbit heights in LEO are identical. Therefore, it may be a productive area for future research to investigate the heterogeneity of impacts from debris mitigation policies for satellites at different orbital heights.

6. Limitations and extensions

There are several potential extensions to the model. Firstly, the model makes a simplifying assumption that satellites can only be launched into one orbit. Different orbits with heterogeneous characteristics (such as the probability and cost of deorbiting, and profitability for a given type of satellite) would allow for more nuanced satellite operator decisions of ‘where to launch’ in addition to the binary decision of ‘whether to launch’ presented to operators in this model.

Secondly, allowing operators to extract profits over multiple time periods, as well as launching more than one satellite to introduce further heterogeneity into the model, such as the influence of large operators with potentially many launches, could reveal interesting dynamics. Another extension could explicitly model operators’ choices to adhere to relevant legislation that is being imposed in order to manage the space debris risk, where a fine could be imposed in the case of non-adherence (if caught) while adherence would involve an initial additional fixed cost but no fine. For example, not adhering to the legislation may be preferable for some operators if their fixed cost of delivering a satellite to orbit is higher compared to other operators.

We can also consider introducing heterogeneity among certain parameters. The fixed cost (C) could be varied between operators to allow for further differences in the type of satellite that is being launched. Furthermore, allowing profits to grow over time or at differing rates between operators, and allowing insurance proceeds to offset collision losses could further provide interesting insights. Finally, the way that the proportion of satellites that are deorbited (θ) is modelled could be modified, such as applying it to all satellites that are in orbit at each time period rather than just within a single time period.

7. Conclusion

The growing problem of space debris has received significant attention in recent years as the growing mass of objects launched into space continues to increase and private companies represent an increasing proportion of the global space industry. However, discussions have mainly centred on the various options of debris mitigation, and the relative benefits associated with their implementation, taking the space industry as a collective. There have been relatively fewer studies that focus on how individual operators’ economic incentives are affected by the imposition of debris mitigation policies.

In this study, we construct an economic model that characterises individual private operators’ decisions to launch. We use the model to simulate the impact of changes to the fixed cost of delivering a satellite to orbit and the proportion of satellites that are deorbited.

We find that the implementation of these policies alters the composition of the space industry, where less profitable operators (and the activities they undertake) are more likely to be forced out of the industry due to the increased costs associated with adhering to the imposed debris mitigation policy.

We also identify a trade-off for policy makers to consider between increasing the number of satellites that are deorbited and the cost levied on private operators. For a given collision probability, higher costs make it less likely that operators will launch. Put differently, private operators will stop launching at a lower collision probability than in the absence of debris mitigation policies. We find that changes in welfare associated with the implementation of debris mitigation policies will depend on the relative parameter values of the fixed cost of delivering a satellite to orbit and the proportion of satellites that are deorbited.

Policy makers should therefore consider the trade-off between increasing the amount of debris that is deorbited with the cost of the policy that is levied on private operators. The cost of removing satellites from orbit may need to be subsidised for policies to lead to welfare gains.

This paper contributes to the literature on the impacts of debris mitigation policies, specifically analysing their impact on the economic incentives of satellite operators. Using economic theory, it provides a number of important insights for policy makers to consider when implementing debris mitigation policies.

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