UNDERSTANDING THE EFFECT OF POST MISSION DISPOSAL BONDS ON THE FUTURE SPACE DEBRIS ENVIRONMENT

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ABSTRACT

For decades, there has been more space debris in orbit than operational satellites. In recent years, however, the use of space has changed dramatically. Launch rates are now approximately 20 times higher than they were two decades ago, when the Inter-Agency Debris Coordination Committee (IADC) published its widely adopted Space Debris Mitigation Guidelines. Despite this growth in activity, the adoption of debris mitigation measures has not kept pace. As a result, there is increasing pressure across the space community to strengthen regulations and explore new mitigation strategies. This study takes a transdisciplinary approach—drawing from economics and the social sciences as well as engineering—to evaluate whether fiscal interventions can support the long-term sustainability of space.

We assess the effectiveness of a Post-Mission Disposal (PMD) bond in reducing space debris in Low Earth Orbit (LEO), using an integrated assessment framework that integrates the Orbital Debris Propagators Unified with Economic Systems (OPUS) model and a source-sink debris model (MOCAT-pySSEM). Over a 25-year simulation, we apply active-lifetime bonds ranging from \$100k to \$800k per satellite, under both 5-year and 25-year PMD rules. Results are also compared to an Orbital Use Fee policy, similar to a tax.

Our findings show that even the smallest bond (\$100k) reduces derelicts by 10.7% relative to a no-policy baseline, with bonds above \$300k achieving reductions of up to 18.6%. However, we find that applying a bond under a 25-year PMD rule is less effective. In this scenario, operators tend to comply by disposing at 520 km—a naturally compliant orbit—but atmospheric drag at this altitude is insufficient to remove derelicts quickly, resulting in debris buildup. In contrast, under a 5-year PMD rule, disposal at 400 km allows debris to be naturally cleared due to stronger atmospheric drag, preventing long-term congestion.

The results demonstrate that a PMD bond is an effective tool for improving compliance, especially for non-naturally compliant orbits where current compliance levels are around 65%. Notably, even small bond amounts significantly improve behaviour. At the highest bond level (\$800k), compliance reaches levels that create a cleaner orbital environment, reducing collision risk and drives more launches than a no-policy scenario. This is an encouraging outcome, suggesting that a well-designed bond can enhance sustainability without stifling innovation or access to space.

Keywords: Space Debris; Post-Mission Disposal, Sustainability, Space Policy.

1. INTRODUCTION

For decades, the amount of space debris in orbit has exceeded the number of operational satellites [1]. In recent years, the use of space has changed significantly. Launch rates are now approximately 20 times higher than they were 20 years ago, when the Inter-Agency Space Debris Coordination Committee (IADC) published its Space Debris Mitigation Guidelines [2], the most widely recognized international document on the subject. However, the adoption of mitigation measures has not kept pace with the increasing launch activity. In response, the European Space Agency (ESA) has introduced the "Zero Debris" approach, which aims to significantly limit the generation of debris in Earth and Lunar orbits by 2030 for all future missions [3].

By 2030, the number of active satellites could range between 100,000 and 1 million, primarily due to the deployment of large Low Earth Orbit (LEO) constellations [4]. Long-term simulations indicate that, even with modest extrapolations of current launch trends, by 2225, there could be approximately 600 cumulative collisions and around 150,000 trackable objects larger than 10 cm [5]. Similar to terrestrial ecosystems, LEO is a common-pool resource system with finite space and limited spectrum allocation, and the new space era could lead to a "tragedy of the commons" [6]. There are lessons learned that we can draw from environmental economics, including the potential of fiscal instruments for regulation that are used in climate, marine, and air pollution. These types of mitigation and regulation can then be applied to the space environment, as an example, processes of adaptive management and governance to assess new large constellations and their potential impact [7].

Economic theory applied to the space environment has a long lineage. The first peer-reviewed economic model specifically addressing orbital debris did not appear until 2015, when Adilov demonstrated how a single actor's activities can generate debris and impose costs on others [8]. Since then, Integrated Assessment Models (IAMs)—which couple socio-economic theory to physical systems— have been employed to explore diverse topics in orbital management. These range from studying the effects of an orbital-use fee [9], assessing the carrying capacity of LEO [10], demonstrating game theory approaches to active-debris removal (ADR) [11], to understanding satellite design choices for in-orbit servicing (IOS) [12] and others [10, 13, 14]. In 2023, Rao et al. [13] introduced the Orbital Propagator and Unified Economics Systems (OPUS) model, the first IAM to apply economic theory to multiple orbital shells and explicitly consider economic launch decisions at different altitudes. OPUS is both open-source and physics model-agnostic, allowing researchers to incorporate its economic framework into various debris models [13].

A major source of debris in LEO is the failure of missions to complete Post Mission Disposal (PMD) after the end of successful operations of a satellite. Derelict satellites can cause collisions or fragments [15], producing large increases to the debris population. Current Inter Agency Debris Committee (IADC) guidelines suggest deorbiting within 25 years. Some regulators implement stricter limits, including the US Federal Communications Committee (FCC) who enforce a 5-year PMD limit. While regulators have focused on PMD time limits, modelling shows that compliance with PMD requirements is more critical than merely shortening the time-frame [16]. In LEO, compliance rates remain below the 90% IADC guideline, and in 2025, the IADC estimated that for satellites launched from 2017 onward, the combined compliance rate for non-naturally compliant satellites was only 65% [17].

For terrestrial resource management and regulation, bonds has been applied as a fiscal intervention in many sectors (e.g. [18, 19]) and recently, in the space sector to support the active debris removal (ADR) market. Manelli et al. [20] argued for a Space Debris Retrieval Bond (SDRB), in which a surety or performance bond—issued by a third party such as a government, insurance company, or bank—ensures the successful completion of a mission. Adilov [21] analysed the space debris bonds economically, demonstrating that bonds can serve as effective deorbiting incentives and could financially support ADR.

In this study, we propose PMD bonds as a policy mechanism to reduce derelict satellites and other debris to ultimately improve the long-term sustainability of LEO. They are an attractive option as they provide a possible funding source for ADR, and offer a financial incentive that could strongly increase compliance. Indeed, PMD bonds have been highlighted for their marketability [21] and because they potentially lower barriers to entry to space compared to a purely tax-based system, by acting as a deposit secondary markets can be used to cover the costs for smaller businesses [9].

Under our modelled proposal, operators would pay a bond of fixed cost per satellite, which is returned (along with interest equivalent to the market rate of return), upon successful disposal of their satellite. In the event that the satellite does not complete post-mission disposal within the provided time threshold, the bond is forfeited, the value of the bond can then be used for In Orbit Servicing (IOS) and/or ADR. The interest means that bonds are non-distortionary for economic decision-making, as the operator's are fully compensated for the foregone time value of money.

To evaluate the effectiveness of the proposed PMD bonds, we port the Orbital Propagator and Unified Economics Systems (OPUS) to Python and integrate it with the latest version of the MIT Orbital Capacity Assessment Source-Sink Evolutionary Modelling Framework (MOCAT-pySSEM). By coupling these technical models, we analyse how a PMD bond can affect operator decisions and, consequently, the future debris environment. We simulate a no-bond as a baseline scenario, then apply a varying levels of bonds per satellite ranging from \$100k to \$800k. For each scenario, a 5yr and 25yr PMD rule is applied for comparison. Finally, the proposed policy is compared to Orbital Use Fees (OUFs) to observe key differences.

Our results show that, any bond is effective at increasing compliance and reducing the number of derelicts in LEO. The lowest bond modelled, \$100k, will reduce the number of launched satellites by 120 and derelicts by 350 at the end of a 25-year simulation, relative to the no-bond scenario. The highest bond modelled, \$800k, increases the number of satellites launched by 50 relative to the no-bond baseline, despite the bond cost to the operator. This occurs because the space safety benefits of fewer derelicts increases the rate of return for launching additional satellites, despite the cost of the bond requirement. We find that the high bond cost leads to very high PMD compliance in most orbits.

Our results demonstrate that any bond implementation effectively increases PMD compliance and reduces the number of derelicts in LEO. Even the smallest bond modelled, \$100k, results in a 10.7% reduction in derelicts, while bonds exceeding \$300k achieve reductions of up to 18.6%. However, there are little changes in the total number of launch satellites, and at a \$800k bond, launch numbers increase compared to the baseline. This occurs because the reduction in debris lowers the risk of collisions, improving space safety and increasing the expected return on investment for satellite operators, despite the added cost of the bond. Furthermore, all bond scenarios improve long-term sustainability, with the largest reduction in the Undisposed Mass Per Year (UMPY) metric reaching 26.6%, indicating less debris at higher altitudes.

Importantly, our results also show that implementing a 25-year PMD rule alongside a bond system reduces the long-term sustainability of LEO. Satellite operators tend to place their satellites at the highest compliant orbit to maximize operational lifetime and minimize fuel consumption. However, at around 520 km, atmospheric drag is insufficient to remove these objects at the same rate they are being deposited. As a result, debris accumulation increases, raising the risk of potential collisions. Conversely, under a 5-year PMD rule, this issue does not arise. At the last compliant altitude of 400 km, objects experience a sufficient atmospheric drag force to remove satellites as quickly as they are deposited, preventing long-term debris build-up.

Finally, we compare the bond to an orbital use fee (OUF) and show that it is more effective in improving the long-term sustainability of LEO, as it improves PMD compliance without incurring the same deadweight loss associated with a universal increase to the cost to launch.

This paper is structured as follows: Section 2 provides background information and a detailed overview of fiscal interventions, including bonds, and their applications in the space sector. Section 3 introduces the OPUS model. Section 4 presents the simulation results and discusses their implications. Finally, Section 5 summarizes the key findings and outlines directions for future research.

2. FISCAL INTERVENTIONS TO THE ORBITAL ENVIRONMENT

Orbital debris from PMD non-compliance is a negative externality to the space environment. Debris left behind by an operator incurs cost and risk to other operators and their governments, who must track and manoeuvrer to avoid large debris and accept the cost of untracked small debris risk. The modelling by [8] found that the current competitive market generates more debris than is economically efficient, as operators do not internalize the cost associated with debris they produce absent appropriate policy intervention. Many market-based instruments that have been applied terrestrially have been proposed to reduce the production of space debris. They mainly focus on three core areas: prevention, which focuses on stopping debris creation by preventing certain access to the space environment, e.g. through a launch tax [22]; mitigation, which reduces the risk of debris generation during operations [23]; and remediation, which decreases risk by moving or removing debris, via interventions such as space-debris removal bonds [20].

Across these three areas, tax is often the main market mechanism proposed. A space debris tax can be applied at multiple points during the lifetime of a satellite: at launch [24], in orbit [9], or at the point of debris formation [25]. Many options have been presented from both economic and engineering perspectives; however, tax is often criticised as 'stifling innovation' as it forces an extra cost onto emerging or established companies. A launch tax is nothing new; an early example was implemented in USA in 1991 to support costs and improve launch sites [26], then in 2020, Australia proposed a launch tax for domestic launches, with a price tag of USD 189,894 per launch (Fees for activities under the Space (Launches and Returns) Act 2018. 2019-2020). The US policy was implemented but was quickly terminated, and in Australia the legislation never made it through parliament [26].

The goal of a market-based mechanism, such as a bond or tax, is to internalise the externality of space debris and reduce the economic inefficiency caused by operators not bearing the full cost of their debris creation. An effective policy should incentivise responsible behaviour without significantly distorting the equilibrium level of space activity. By ensuring that operators account for the risks and costs associated with failed PMD, such a system encourages compliance while maintaining efficient market outcomes.

2.1. Space Debris Retrieval Bonds

Bonds for environmental management is not novel and has a long lineage (see [18, 19]). More recently, this concept has been proposed using the insurance sector as a medium [20] and also analysed economically when applied to space debris [21].

The concept is relatively simple, a surety or performance bond is issued by a third party (can either be a government, insurance company or a bank) and is to guarantee a successful completion of a mission. An underwriter then guarantees an amount equal the decommissioning sum in return for an arrangement fee and premium [20]. The trigger is then either from an operational issue, such as a failure of a satellite, followed by the financial inability of the principal to remedy the issue (in practice, this means the insolvency of the principal) [20].

For this research, we propose a slightly different policy mechanism. As aforementioned, the risk posed by the environment to an active satellite is varied across LEO depending on the number of , trackable and non-trackable debris, and this should be reflected in the cost of launching to that orbit. Secondly, rather than relying on a secondary market (insurance), we propose an escrow system, where an orbital use fee [9] is collected by the launching state, the risk of an orbit is determined through a chosen metric (e.g. [27–29]). The pot of money is invested at market interest rates and on a successful attempt of a PMD, the full contribution is then returned to the operator. On failure, an assessment is made on the damage posed and fees are used either for IOS or ADR. An overview is provided in Figure 1.

Policy Overview

1. Bond cost is set by the launching state and applies for the operational time only.
   - Higher risk orbits *could* vary bond cost.
2. Escrow is collected and (usually) managed by third party. Gains market-rate interest.
   - Payment can be made in full or annually.
3. On a **successful mission** total amount is returned to operator.
   - Deductions can be taken: Poor behaviour (not sharing position/velocity/covariance data). Administration fees.
4. On a **failed attempt** to post mission dispose (PMD) a panel will review the mission.
   - Percentages can be returned based on attempt/no-attempt.
   - Unused funds are given to Active Debris Removal (ADR) or In-Orbit Servicing (IOS).

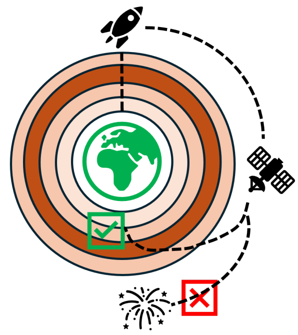

Figure 1. Overview of the Post Mission Disposal Bond Policy

3. ORBITAL PROPAGATORS UNIFIED WITH ECONOMIC SYSTEMS (OPUS)

In 2023, Rao et al. [13] introduced Orbital Propagators Unified With Economic Systems (OPUS), a framework that integrates orbital dynamics with the economic decision-making of space actors. By incorporating policy incentives into its simulations, OPUS facilitates the study of second-order effects—such as how shifts in operator behaviour may amplify or mitigate debris risks. The original version was written in MATLAB and demonstrated with two environmental models: a four-species version of MOCAT-SSEM (MOCAT-SSEM 4S) and a Gaussian mixture probability hypothesis density (GMPHD) model.

OPUS is model-agnostic and comprises two main components: an economic module and a debris module. This design allows researchers to substitute or upgrade the underlying debris models. Recently, MOCAT-SSEM has evolved into a Python-based, object-oriented platform (MOCAT-pySSEM) that supports numerous features that enhance modelling flexibility and accuracy. To remain compatible with these advancements, OPUS was also migrated to Python, enabling direct integration with the latest MOCAT-pySSEM package. In the following section, we describe these debris and economic components.

3.1. Debris Model

Numerous debris models have been developed to provide predictions of the long-term space environment. These models generally fall into two categories: statistical sampling approaches, such as Monte Carlo (MC) methods ([30**?** –32]), and source-sink models, often referred to as particle-in-box (PIB) models [33–35]. Other fast evolutionary models have also been developed, using Network Analysis [36] or using continuum formulations for density propagators [37]. MC methods are considered the industry standard [38] due to their higher fidelity, as they propagate all objects individually using semi-analytical techniques. However, this comes with high computational cost and long run times. As an example, Rosengren et al. [39] propagated 19 million orbits -with no collision assessments- over a 120-year period, requiring an equivalent of 24 years of CPU time. An PIB model takes minutes to hours and can be run on a personal laptop, or in a web browser [35].

IAMs and other interdisciplinary models, such as OPUS, require rapid propagation and assessment of the orbital environment. This is because economic models often incorporate optimizers to determine optimal launch strategies, necessitating multiple catalogue-wide propagations per time step. Given these computational demands, PIB models are a suitable choice for modelling the debris environment.

3.1.1. MOCAT-pySSEM

MOCAT is a suite of orbital debris tools that aim to provide multiple different open-source debris models each with a different use case. MOCAT-SSEM is the fastest model but, the lowest fidelity. Originally written in MATLAB [1], MOCAT-pySSEM [2] is the python fork and the currently maintained codebase [40].

The model focuses on aggregate trends rather than indi-

[1] https://github.com/ARCLab-MIT/mocat-ssem/
[2] https://github.com/ARCLab-MIT/pyssem/

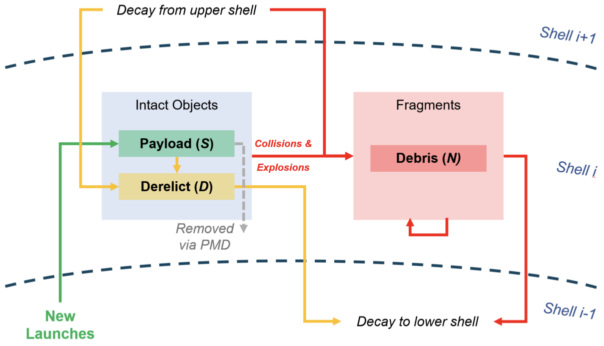

Figure 2. Qualitative schematics of the MOCAT-pySSEM model

vidual object specifics. LEO is split into altitude *shells* and *species*. In this context, species refers to classes of objects, split by characteristics such as mass, radius or their object type. Examples of species could include satellites, debris or rocket bodies. Figure 2 presents the relationship between species and orbital shells, with a simplified set of species. For each orbital region, defined by an altitude range and divided into n_h orbital shells, each with a thickness of d, these objects can be classified into either *sources* or *sinks*

$$\dot{P}_{h_i} = \dot{\Lambda}_{h_i} + \dot{C}^{PMD}_{h_i} + \dot{F}_{h_i} + \dot{C}_{h_i} \tag{1}$$

for $h_i \in \{1, 2, \cdots, n_h\}$, where the change in the population of each P species, $\dot{P}$, is a function of launch rate, $\dot{\Lambda}$, post-mission disposal, $\dot{C}^{PMD}$, atmospheric drag, $\dot{F}$, and collisions, $\dot{C}$ [7].

For each active satellite species, it is typical to simulate a fraction of satellites being de-orbited from each altitude bin at each time step, based on their assumed operational lifetime, Δt, to account for deliberate post-mission disposal. For the corresponding debris category associated with each active satellite type, a percentage of post-mission disposal failures is modelled to occur at each time step, reflecting the likelihood that some satellites will fail to execute their planned de-orbit procedures.

$$\dot{C}^{PMD} = \frac{1 - P_M}{\Delta t} P_i \tag{2}$$

with a probability of success equal to P_M. Atmospheric drag is modelled as in previous work [33], with inactive objects and active objects without propulsion experiencing drag according to:

$$\dot{F} = \left[\dot{F}_{d,P_1}, ..., \dot{F}_{d,P_N} \right] \tag{3}$$

where $\dot{F}_{d,P}$ is written as follows for species with drag:

$$\dot{F}_{d,P} = -\frac{P_+ v_+}{d} + \frac{P v}{d} \tag{4}$$

In Equation 4, d is the thickness of an altitude bin, the subscript '+' indicates quantities related to the bin immediately above the current one, and v is the rate of change of the semi-major axis, expressed as:

$$v = -\rho B \sqrt{\mu R} \tag{5}$$

where $B = c_D \frac{A}{m}$, defaulting to a flat-plate drag coefficient of $c_D = 2.2$ [34], but can also be defined by the user. A is the drag area of the object, and m is the mass of the object. Atmospheric density ρ can be computed in MOCAT-pySSEM using a chosen density model [41, 42].

3.1.2. Collisions

A fundamental element of any debris model is calculating the probability of collision and the consequent number of fragments. In the SSEM framework, each species is uniquely paired with others, representing the set of potential collisions pairs in the simulation. The collision rate for species i denoted as $\dot{C}_i$ is given by:

$$\dot{C}_i = \sum_{k=1}^{N_s} \Gamma_{ij} \phi_{ij} P_i P_j + \dot{C}_{i,\text{add}} \tag{6}$$

This equation indicates that in each shell and for each collision species pair, the primary and secondary collision species lose objects to collisions at a rate based on the behaviours of the two species Γ_{ij} and the physical geometry of the objects and shells ϕ_{ij}. For debris species, the population is potentially also increased by the output of collisions between other species pairs, $\dot{C}_{i,add}$.

Γ_{ij} is a matrix that quantifies the likelihood of a collision between species P_i and P_j, generally beginning with a value of -1, to reflect that the species in that shell is decremented by one during a collision, and additional terms that modify collision probability to reflect factors like orbit coordination for mutual physical separation and collision avoidance manoeuvrer efficacy. For example, in the case of two manoeuvrable slotted satellites species Γ_{ij} may be set to zero under the assumption that two satellites within the same constellation will not collide.

$$\phi_{ij} = \pi \frac{v_r(h) \sigma_{ij}}{V(h)} \tag{7}$$

Equation 7 represents the physical aspects of collision probability subject to a kinetic theory of gases assumption. $V(h)$ and $v_r(h)$ are the volume of the altitude shell and the average velocity of the shell. σ_{ij} is a function of radius of the colliding objects, r_i and r_j:

$$\sigma_{ij} = (r_i + r_j)^2 \tag{8}$$

Finally, $\dot{C}_{i,add}$ represents the additional fragments generated from a collision (n_f) based on its impact velocity. For each collision, if the impact velocity is above 40 J/g then it is considered to be catastrophic. The number of fragments are calculated from the NASA Standard Break Up Model [43] and then are binned back to each species by their mass.

3.2. Economic Model

At each time step of a simulation, OPUS uses pySSEM to understand the position of the debris, satellites and rocket bodies in LEO to predict economically-informed demand for access to orbit for new satellites. This includes the number of different species and the potentially active loss rate of being in a shell, which is a proxy for collision risk. The economic model assumes an open-access setting, where anyone can launch in LEO, given that the revenue to cost ratio of a operation is equal (i.e that an operator will not lose money for operating a satellite in space). A detailed overview of the model is explained by Rao et al., [13], it does not have the ability to currently model PMD bonds, which has been added and is explained in the next section.

The model focuses around a fringe satellite, i at a given orbital shell k. This satellite has a collision likelihood $P_{i,k}$ with all objects currently in this orbit and will have an active lifetime that it must operate Δ. These fringe satellites are launched from operators into the "competitive fringe". Operators in the fringe each control relatively few satellites compared to the constellation operator and are assumed to behave according to a system of "open-access conditions". The open-access conditions are the key innovation in OPUS.

Under open access, this satellite operator will earn zero economic profits in equilibrium at any location that it can access. For all shells, $\forall k$, the fringe will launch $\hat{X}_{2kt-1}$ until the the following system of equations is satisfied across all locations of k:

$$\forall k, \quad \hat{X}_{2kt-1} : R_k(S_{2t}) - r - \Delta - P_{2k}(S_{\cdot t}, D_{\cdot t}) - \tau_{kt} = 0. \tag{9}$$

Where $R_k(S_{2t})$ is the gross rate of return earned by a satellite given economic competition within the fringe industry, r is the discount rate representing the opportunity cost of funds, and τ_{kt} is a location-time specific tax rate, or orbital use fee [9].

We assume the constellation's launch plans are publicly announced in advance and are exogenous to the fringe's choices. P_i is calculated from the same model that computes S_i and D_k. The net rate of return function has two components: the expected future revenues or payoffs that the satellite delivers in period t, $q_k(S_{2t})$, and the annualized unit cost of deploying it, c_k:

$$R_k(S_{2t}) = \frac{q_k(S_{2t})}{c_k}. \tag{10}$$

The revenue generated from being at a given altitude, k, is determined by a revenue function that is linear in the aggregate number of fringe satellites, with a common coefficient across all altitudes

$$q_k(S_{2,t}) = \alpha_1^q - \alpha_2^q \sum_{k \in K} S_{k2t} \tag{11}$$

The parameters of the revenue function are set to match the following conditions following [13]:

1. The maximum willingness-to-pay for service from a fringe satellite is $\alpha_1^q = 7.5 \times 10^5$ \$/sat.
2. Fringe satellites at all locations are perfect substitutes, and willingness-to-pay for service from a marginal fringe satellite declines at $\alpha_2^q = 100$ \$/sat.

The cost function reflects three main factors. The lift price c_{lift} is the dollar cost per kilogram of accessing LEO, multiplied by the mass of the satellite payload. We set the lift price to \$5,000 per kg following the vehicle-weighted launch price index developed in [9].

Secondly, the cost of delta-v budget given a given altitude $c_{\Delta v}(k)$. This delta-v required to maintain a satellite in its target orbit and conduct any necessary manoeuvrers over its lifetime. Letting $v_{drag(k)}$ be the force exerted on the satellite by atmospheric drag and the altitude, k.

The opportunity cost of lifetime due to deorbit from altitude k to altitude k^*, $c_\mu(k, k^*)$. This is the cost of a satellite's lifetime being reduced by expending fuel to deorbit.

Finally, letting the rate of non-compliance with deorbit regulations be ϕ, the complete cost function, for an altitude of k given a target deorbit location k^* is:

$$c_k = c_{\text{lift}} + c_{\Delta v}(k) + (1 - \phi) c_\mu(k, k^*) \tag{12}$$

4. METHODOLOGY

Using the updated Python OPUS model, we are able to test the efficacy of a policy intervention such as post-mission disposal bond. Unlike the initially proposed PMD insurance bonds [20], we have selected a few policy changes. We propose an escrow system, where an orbital use fee [9] is collected by the launching state and the risk and price is determined through a chosen metric (e.g. [27, 28, 44]). The money is invested at market interest rates and on a successful attempt of a PMD, the full contribution is then returned to the operator. On failure,

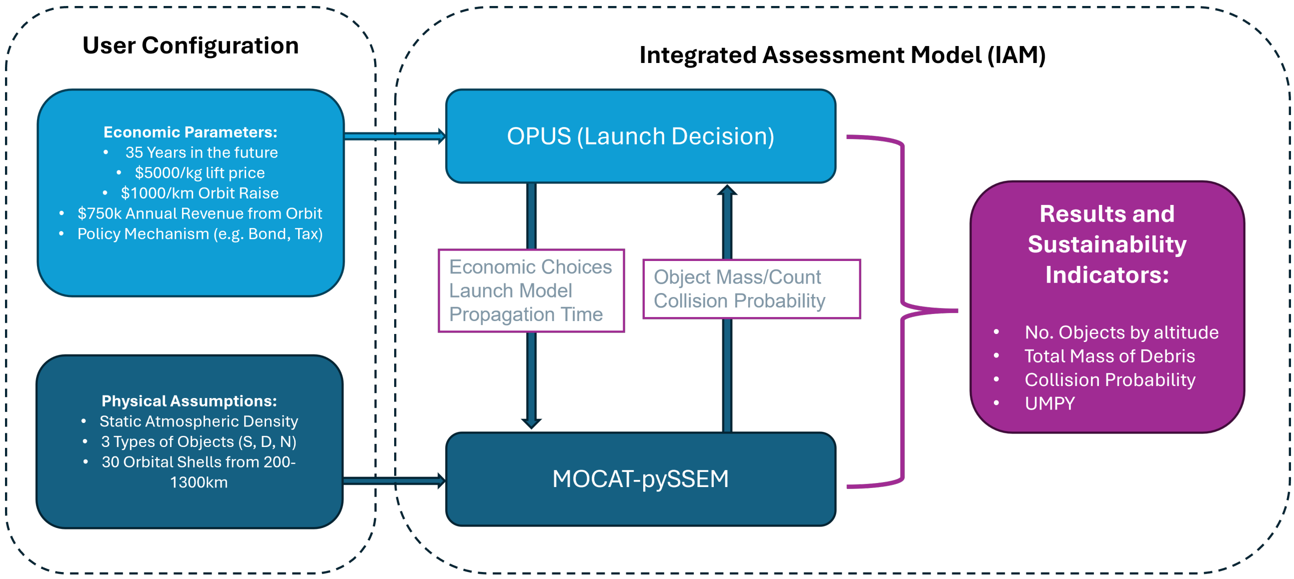

Figure 3. The integration and configuration of OPUS and pySSEM. UMPY is the Undisposed Mass per Year [44].

an assessment is made on the damage posed and fees are used either for IOS or ADR. Secondly, the risk posed to an active satellite varies across LEO and therefore should be reflected in the price of the bond.

4.1. An economic model for Post-Mission Disposal Bonds

4.1.1. PMD Compliance

We have implemented Adilov's [21] first proposition, which derives for a satellite in orbit the minimum value of the bond, $b*$, needed to fully incentivise deorbiting after their active lifetime, Δ.

$$b^* = \alpha_1^q \left[\frac{1-\beta^\lambda (1-w)^\lambda}{1-\beta(1-w)} \right] \beta^\Delta (1-w). \tag{13}$$

$$= \alpha_1^q \left[\frac{1-\beta^\lambda}{1-\beta} \right] \beta^\Delta. \tag{14}$$

where the discount factor β accounts for opportunity cost of time and is related to the discount rate via $\beta = \frac{1}{1+r}$. α_1^q is per period willingness-to-pay for service from a fringe satellite, or revenue (Eq. 11). λ is related to the opportunity cost of deorbiting, expressed in years of foregone mission lifetime due to deorbiting. Δ is the mission lifetime (expressed in years). Adilov considers a varying level of failure rate of a satellite, w, however, here we assume no random failures during active lifetime. Therefore, the value of b^* can be simplified to Equation 14.

The relationship between rate of PMD compliance, $C(b)$, and the dollar cost of the bond can be expressed for non-naturally compliant orbits as:

$$C(b) = P_M + [\frac{(1-P_M)b}{b*}], \text{if } b \neq 0, \tag{15}$$

Where P_M is the baseline rate of PMD success. If β is 0, then all fringe satellites comply at 65%, which is the current rate for satellites in objects that are not naturally compliant from the last decade [5].

4.1.2. Bond Cost to Operator

A bond is only applied to non-compliant orbits, which can be configured with either 5 or 25 year post-mission time limit for compliance. A bond is an additional cost for the operator that influences their decision to launch and will affect their rate of return for each orbital shell, $R_k(S_{2t})$. The cost of the bond can then be applied to Equation 9, note the tax term has been removed:

$$\forall k, \quad \hat{X}_{2kt-1} : R_k(S_{2t}) - r - \mu - P_{2k}(S_{\cdot t}, D_{\cdot t}) - \beta = 0. \tag{16}$$

In OPUS, this will only apply to non-naturally compliant orbits. Lifetime is calculated using a static atmospheric density model [41]. Figure 4 shows the naturally compliant altitudes for 5 and 25 year PMD, a fringe satellite has a mass of 220 kg and a ballistic coefficient of 2.2.

4.2. Simulation Configuration

There are 30 orbital shells from 200-1300 km. pySSEM is configured to have seven species: constellation satellites, fringe satellites, 4 debris and derelict species with

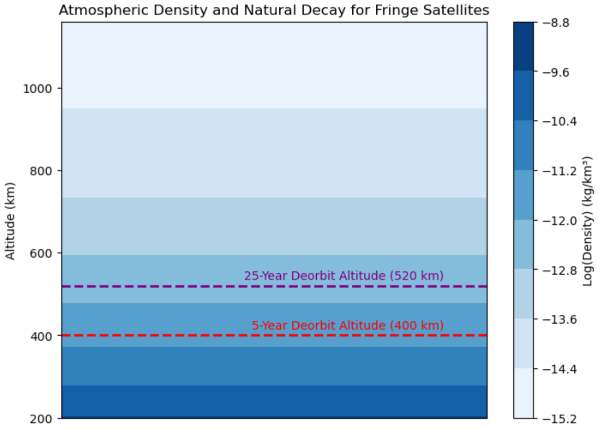

Figure 4. Fringe Satellites Naturally Compliant Orbits, Mass = 220 kg, C_d = 2.2. Atmospheric density values are static through the simulation.

different sizes, and Rocket Bodies. Each species has various parameters that effect their dynamics and collision probability. The parameters of a fringe satellites are shown in Table 1. The model is run from 2025 and for 25 years, the initial population is derived from Two Line Elements (TLEs) from space-track and then binned to orbital shells. Differential Equations are integrated using the Scipy's backward-differentiation formulas.

To evaluate a policy's efficacy for the Long-term sustainability of LEO, we will use a proxy related to the total mass of debris that is added to the environment: Undisposed Mass Per Year (UMPY). It assess the total amount of mass, as a function of orbital lifetime [29]. For satellites that are above the naturally compliant orbit, if they successfully disposed, we assume that they are deposited at the de-orbit altitude. If they are unsuccessful the derelict is left at the operational altitude. This is a pessimistic assumption, as many objects, particularly for large constellations, will undergo propulsive de-orbiting to altitudes that result in demise rather than be deposited at the threshold altitude. UMPY is calculated as:

$$\text{UMPY} = \frac{1}{t_{\text{sim}}} \sum_{i=1}^{n_{\text{objs}}} m_i \left[\frac{e^{X\left(\frac{\text{life}_i}{t_{\text{sim}}} - 1\right)} - 1}{e^{X} - 1} \right] \quad (17)$$

where t_{sim} (in years) denotes the total duration of the study or simulation and n_{objs} represents the number of uncontrolled objects within the system. Each object i has a mass m_i (in kilograms), and a lifetime life_i (in years), which is the period it remains uncontrolled before reentry or removal. Finally, X is a dimensionless lifetime scaling exponent that modifies the effect of life_i within the exponential term. We use X = 4 as suggested by [29].

Finally, as a policy comparison, we then compare an orbital use fee [9] and a tax proportional to the collision risk (τ_{kt}), as in Equation 9.

Table 1. Properties of the $\mathbf{S_u}$ satellite in the MOCAT-pySSEM configuration. CA is collision avoidance.

Property	**Value**
Cd	2.2
Mass [kg]	223
Radius [m]	0.73
Area [m^2]	1.67
Active	true
Slotted	false
Drag	false
Maneuverable	false
Trackable	true
Mission lifetime	5 years
Disposal altitude	Naturally Complaint
Efficacy of CA vs. inactive	1×10^{-5}
Efficacy of CA vs. active	1×10^{-5}
Rocket body	false

5. RESULTS AND DISCUSSION

5.1. Cost to Operator

The total costs to an operator are shown in Figure 5. The costs are presented for a 5-year PMD rule and a $100k bond. The compliance rate for each orbital shell for this bond amount is plotted on the second axis. For comparison, the compliance rate for a $300k bond is also included, but not the corresponding cost.

Orbits below 400 km are naturally compliant, so the costs only include the initial lift price and station-keeping expenses. Above this altitude, costs rise sharply up to 700 km as additional factors come into play. The most significant cost is lifetime loss: this represents the operational time lost due to the need to reserve fuel for deorbiting. This cost reaches a peak of $750,000. The bond cost that increases to the plateau represents the minimum bond required to incentivize the operator to successfully deorbit (Equation 14). At lower altitudes, this cost is lower since less fuel is needed to reach the deorbit line, reducing the opportunity cost. This has an inverse relationship with distance above 400 km.

The compliance rate per orbital shell is compared for total bond amounts of $100k and $300k over a satellite's active lifetime. Below 400 km, the compliance rate is 1 (100%) since satellites naturally deorbit. At 693 km, compliance stabilizes at 0.71 and 0.83 for $100k and $300k bonds, respectively. This means increasing the bond by $200k results in a 10% higher PMD compliance rate at high altitudes. As an extreme example, if the bond were raised to $1 million, compliance rate would approach 1.

Above 400 km, compliance decreases under both bond

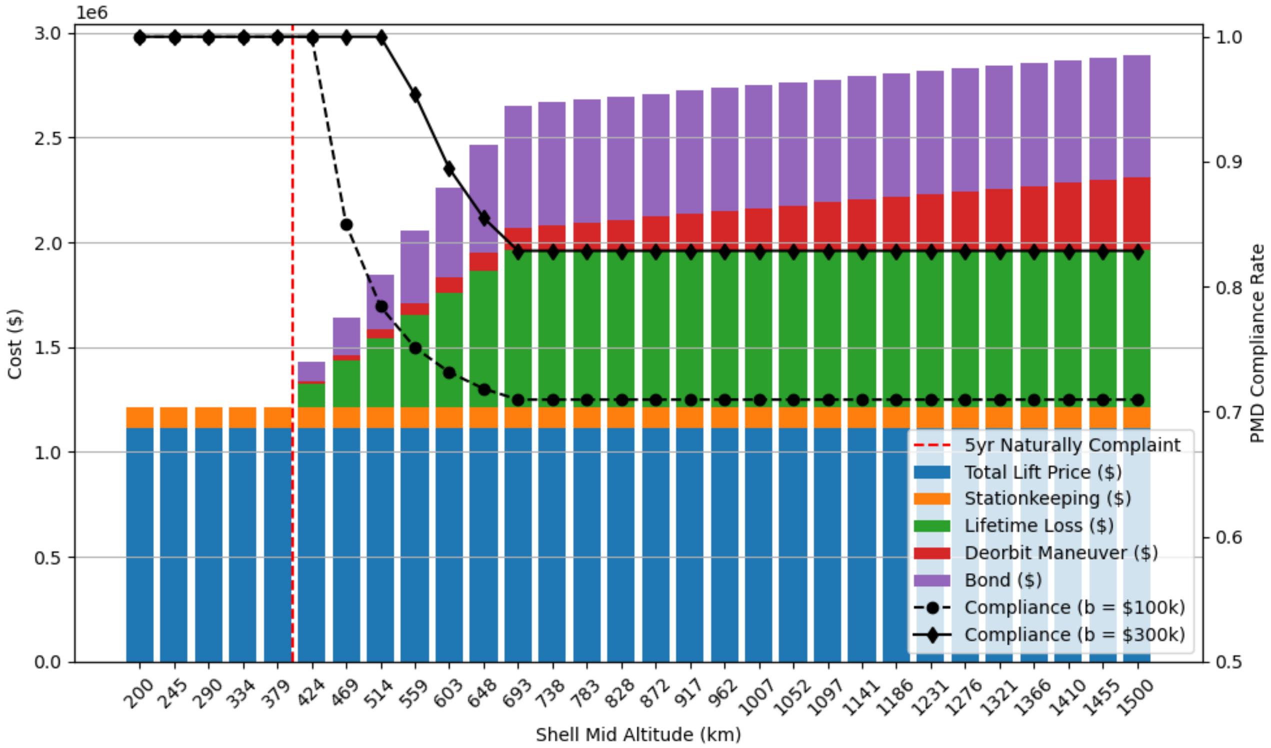

Figure 5. 5yr PMD scenario. For each shell, the total mission cost to the operator is shown. The compliance rate is provided.

scenarios. However, the decline is steeper for the lower bond, as the smaller financial penalty allows more operators to absorb the bond cost instead of ensuring deorbit compliance. Note, for instance that at 514 km by increasing the bond from $100k to $300k, the compliance rate rises from 0.78 to 1, as the higher financial penalty forces full compliance.

5.2. Impact to the Space Environment

A 25-year simulation was conducted to compare the impact of an increasing bond (from $100k to $800k) under both 5-year and 25-year PMD rules. These results are compared against a baseline scenario where no bond is applied. Figure 6 confirms that, for both PMD lifetimes, the number of derelict satellites due to non-compliance decreases as the bond amount increases. Additionally, the number of fringe satellites also declines compared to the baseline, as possibility of loosing the bond due to failure to deorbit deters some operators.

Interestingly, even a small bond improves compliance. A $100k bond results in the largest reduction, preventing 1,000 derelicts by the end of the simulation under the 5-year PMD rule. However, as the bond amount increases, the number of derelicts plateaus after $200k. This suggests that even a relatively small bond is effective in improving PMD compliance, with diminishing returns at higher bond values.

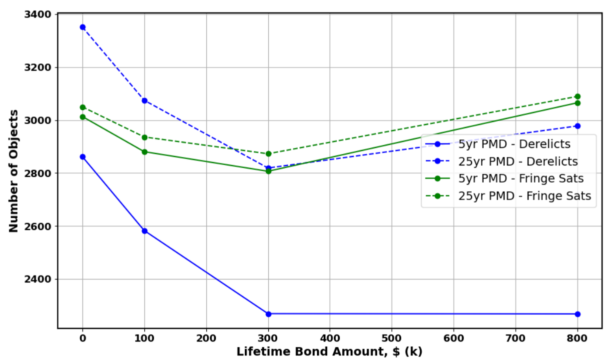

Figure 6. The final number of derelicts and fringe satellites from a 25 year simulation, as the bond increases to $800k.

The reduction in fringe satellite launches from the baseline remains relatively small (200 after 30 years for a $300k bond, indicating that while the bond introduces an additional cost to operators, it does not stifle launch. Furthermore, when the bond amount reaches $800k, an increase in fringe satellite launches is observed under the 5-year PMD rule. This corresponds with a plateau in the number of derelicts, suggesting that a high bond is effective in reducing the number of abandoned satellites. This, in turn, lowers the collision risk, making the space environment safer and leading to an increase in satellite launches. However, this trend does not hold under the

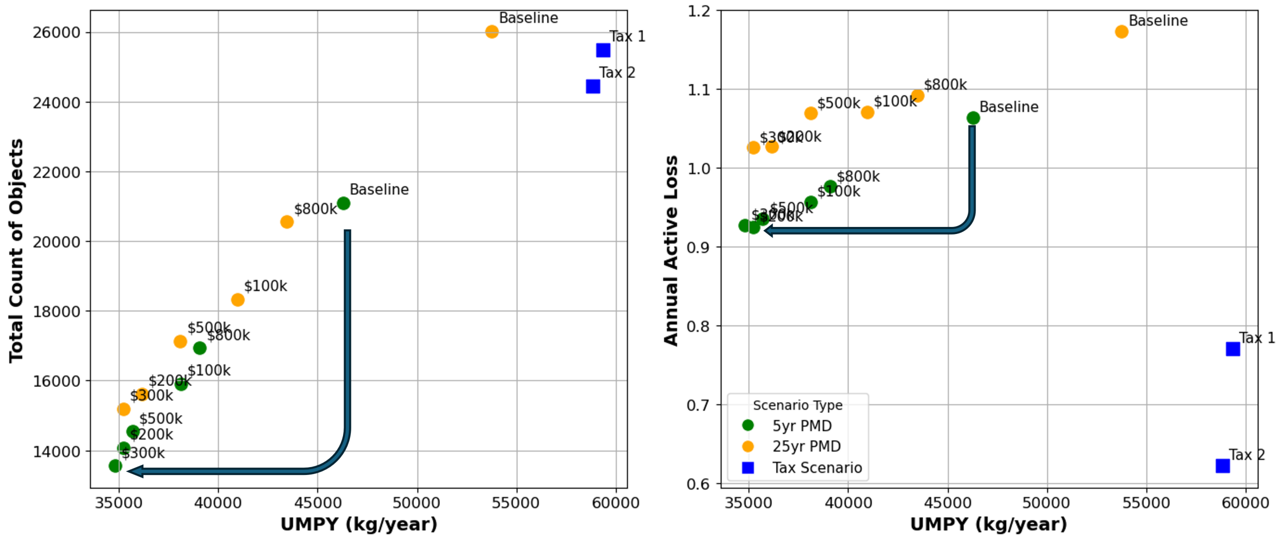

Figure 7. Progressive Improvements to UMPY with increases to the Bond amount. Compared against the total count of objects and the number of active satellites lost to collisions across all shells.

25-year PMD rule, a result explored in more detail in the next section.

Overall, these results reinforce the idea that a bond system —along with the financial incentive of reclaiming the escrow with interest— encourages compliance rather than discouraging satellite launch.

The long-term sustainability impact is assessed using UMPY. Figure 7 presents the final state of the simulation across all 14 scenarios. The final-year UMPY is plotted against both the total number of objects and the final active satellite loss. The active satellite loss is summed across all orbital shells (see Section 3.1.2) and calculated using an indicator variable, it uses collision the equations to understand how many satellites could be lost due to operations given the count of objects in orbit. An active loss of 1, roughly correlates to 1 minor or fatal collision in a year.

As shown in Figure 6, there is a significant improvement across all metrics when comparing a 5-year PMD rule to a 25-year PMD rule. This policy change alone demonstrates a strong positive effect on space sustainability.

Focusing on the 5-year PMD rule, we observe a steady decline in the total object count a small reduction in the active loss metric as the bond amount increases up to $300k. However, at $800k, the total object count rises again, while UMPY continues to decrease. This suggests that the increase in total objects is due to operators relaunching into the cleaner orbital environment created by the bond system, rather than an accumulation of inactive objects. UMPY, which measures the number of inactive satellites, confirms this trend.

For non-compliant orbits, if an operator successfully completes PMD, the satellite converts to a derelict and transferred to the highest non-compliant orbit. Under the 5-year PMD rule, this is 400 km, where atmospheric drag removes derelicts relatively quickly. However, under the 25-year PMD rule (Figure 6), satellites are placed in a "graveyard" orbit after their active lifetime. At this altitude, atmospheric density is too low to remove derelicts at a sufficient rate, leading to an accumulation of debris and an increased number of collisions within the model.

The active loss does not decrease significantly across the bond scenarios. As shown in Table 1, Su satellites are designed to be non-manoeuvrable, meaning they lack collision avoidance capabilities. As a result, despite a reduction in the number of derelicts due to bond implementation, the overall satellite count remains stable. Since each non-manoeuvrable satellite contributes to active loss, this metric remains high even as compliance improves.

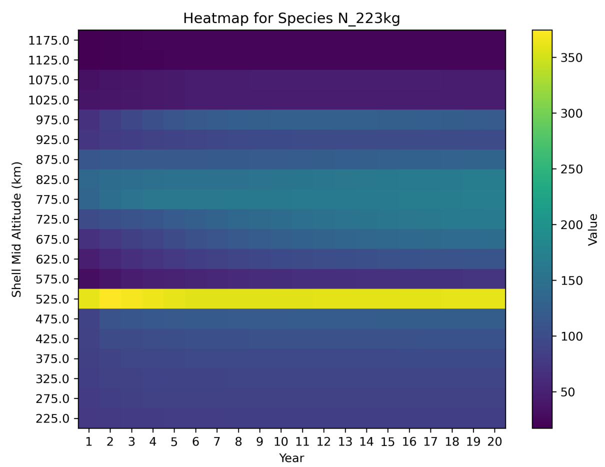

Figure 8. Count over time for each orbital shell. N_223kg is a derlict satellite, with a mass of 223 kg.

5.3. Orbital Use Fee vs Bond

As a policy option comparison, two OUFs are simulated, with no bond implemented and presented in 7. The tax is proportional to the collision risk as outlined by Rao et al. [13], Tax 1 and Tax 2 indicate the scale at which the cost of the tax.

The results show that although the tax reduces the total number of objects in the space environment and the collision risk, the reduction of UMPY is minimal compared to a bond implementation. This is because a tax only is incurred as a cost to the operator, disincentivising launch and although the number of objects will decrease in LEO - the overall compliance rate will remain the same (modelled at the current rate of 65%).

6. CONCLUSIONS AND FUTURE WORK

In this paper, we present a novel result that any Post Mission Disposal Bond will reduce the number of derelicts left in LEO, ultimately, 10.7% for the smallest $100k bond by 18.6% for higher than $300k. All bonds, both applied to 5yr and 25yr PMD rule will improve LTS, with the largest drop of 26.6% of the Undisposed Mass Per Year (UMPY) metric, indicating less debris at higher altitudes. We have also improved the OPUS IAM, through forking the model to Python and integrated it with the object orientated source-sink evolutionary model (MOCAT-pySSEM), allowing a higher fidelity of debris modelling leading to more accurate economic decisions. Secondly, we have implemented Adilov's proposition that defines the relationship between PMD compliance to a bond cost [21].

We first show how that when compared to a baseline scenario with no policy intervention, a $100k bond will decrease the number of fringe satellites by 120 at the end of the 25 year simulation, but will decrease the number of the derelicts by 350. As the bond increases up to a max of $800k, after 25 years we show that the number of fringe satellites increase but derelicts remain the same. The model thus corroborates that a higher bond will improve compliance significantly, which in-turn will drive more launches.

Secondly, as a point of policy comparison, we model two rates of Orbital Use Fees (OUF), highlighting how a stand alone tax will reduce the overall count of debris, but not the compliance to post mission disposal, since there is no economic incentive to, concluding that a bond is a stronger policy.

For future work, although the technical modelling of the bond is complete, there are improvements that could be made to the underlying mechanics of the model. Firstly, only modelling the revenue and cost functions of one type of satellite will likely lead to inconsistencies of where the optimal part of LEO is to launch. We would like to see multiple 'species' of satellites that could be launched. Secondly, pySSEM models only circular orbits and rocket bodies, thus the binning of these objects gives unrealistic distribution of eccentric rocket bodies - this could lead to over estimations of debris in shells. Finally, additional analysis could show how funds collected by non-compliance could fund selected ADR.

ACKNOWLEDGMENTS

This work was funded through the UCL's STFC IAA 2022-25 Impact Acceleration Account. Indigo Brownhall was kindly hosted as a visiting researcher at the Independent Space Safety Office, at the European Space Agency (ESA) ESTEC Offices in The Netherlands, by Dr. Francesca Letizia.

Indigo Brownhall is also funded through the UK Engineering & Physical Sciences Research Council (EPSRC) under the grants EP/R513143/1 and EP/W524335/1.

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