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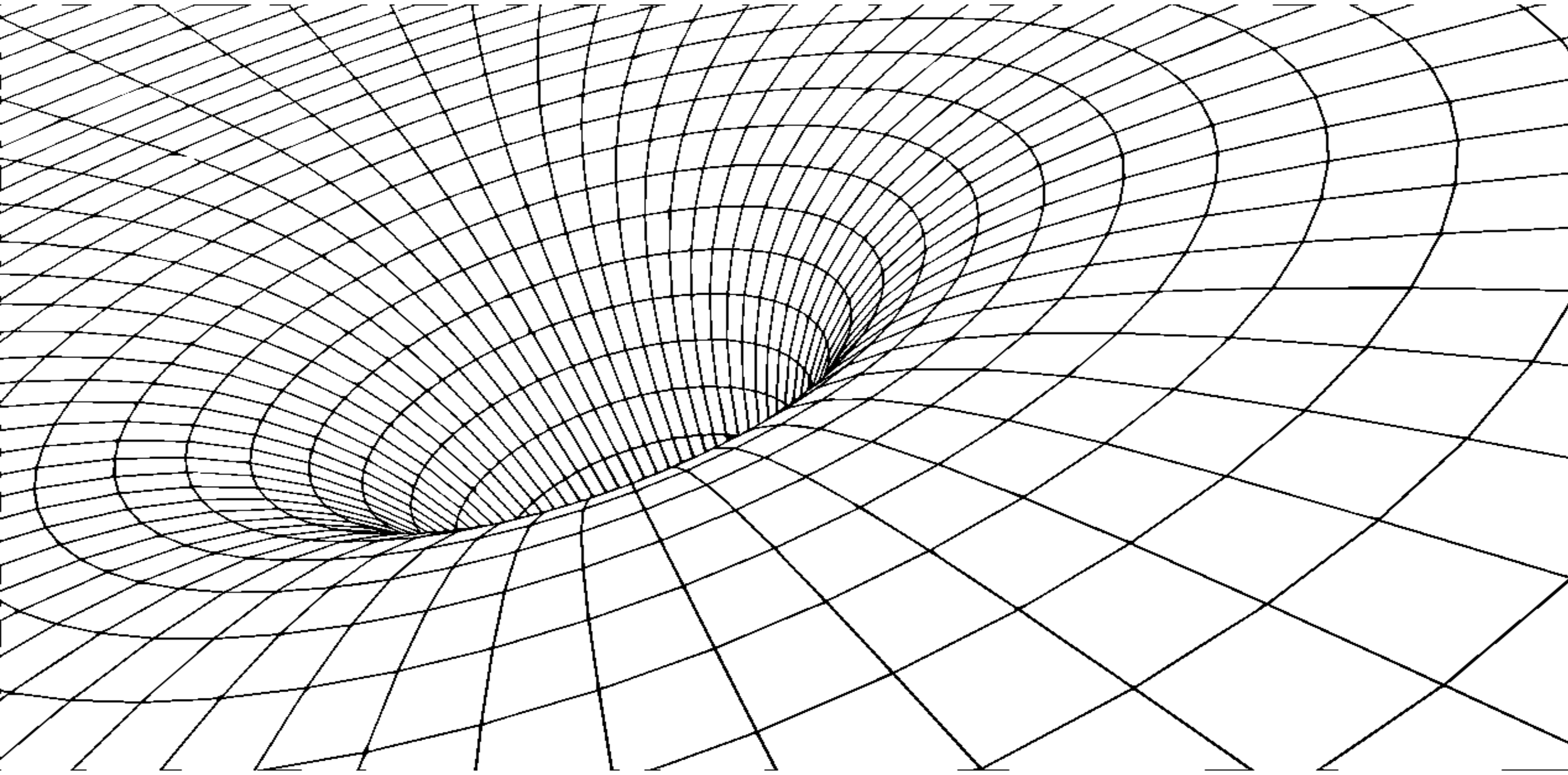

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This paper evaluates optimal active debris removal (ADR) policies for managing space pollution caused by orbital debris. ADR refers to ex post mitigation efforts that involve removing debris from orbit. We extend the DISE-2024 model, an integrated assessment model (IAM) of the global economy and space environment, by incorporating ex-post abatement cost functions for different types of orbital debris. The model determines optimal abatement expenditures and the optimal proportion of debris (derelict satellites, rocket bodies, and fragments) to be removed in order to maximize social welfare. Our findings indicate that the optimal removal rate for small debris fragments is higher than for larger objects such as derelict satellites and rocket bodies. The cost of implementing ADR policies increases over time as space activity expands. Importantly, optimal ADR policies help prevent unlimited accumulation of orbital debris, avoiding the risk of a Kessler syndrome. (JEL Classification: D62; E21; E22; Q53; Q58).

KEYWORDS. Outer space, Orbital debris, Satellites, Abatement cost, Optimal policy, ADR policies.

1. INTRODUCTION

Human activities in spaces including commercial, scientific, and military operations, have increasing the polluted the orbital environment with millions of debris objects. According to the European Space Agency (ESA), more than 140 million human-made objects currently orbit the Earth. The vast majority are small (less than 1 cm in size) and would cause only limited damage if they collided with a spacecraft. However, there are over 1.1 million fragments between 1 and 10 cm, more than 40,000 fragments larger than 10 cm, and over 5,000 large intact objects, including upper stages of rockets and derelict satellites. Debris larger than 1 cm can be catastrophic in a collision with operational satellites due to the

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high velocities involved. Orbital debris is generated not only by launch activities but also through endogenous in-orbit processes such as breakups and explosions of intact objects (e.g., derelict satellites, rocket bodies, and engines), as well as collisions between debris. On the other hand, space debris is self-propagating, as collisions between pieces of debris create more debris. The literature labels this as the "Kessler syndrome," representing a scenario of collisions in a cascade (Kessler and Cour-Palais, 1978; Kessler, 1981).

Given the unique characteristics of space pollution caused by orbital debris, two main types of mitigation policies can be implemented: reducing emissions and actively removing debris from orbit. The former is a passive mitigation strategy aimed at minimizing the release of new debris, while the latter is an active mitigation approach focused on reducing the existing stock of debris already present in orbit. Effectively addressing the issue of orbital debris requires a dual approach: limiting the creation of new debris and actively reducing the current debris population, recognizing that outer space is a global commons. International cooperation and the establishment of a robust legal framework are essential for coordinating these efforts and encouraging responsible behavior in space. Emission mitigation strategies seek to prevent the generation of new debris by establishing guidelines for spacefaring actors. Both the United Nations and national space agencies have developed a range of (voluntary) debris mitigation guidelines. For instance, the European Space Agency (ESA) has introduced a "zero debris" strategy, targeting 2030. These guidelines emphasize improved satellite design standards for end-of-life disposal, such as the safe deorbiting of defunct satellites or relocating them to graveyard orbits. They also promote minimizing the release of operational and mission-related debris, implementing passivation measures to prevent post-mission explosions, and avoiding in-orbit collisions.

In addition to emission mitigation strategies, an alternative policy involves cleaning the space environment by actively removing debris (referred to as negative debris emissions), known as active debris removal (ADR). ADR refers to direct environmental remediation efforts aimed at physically removing pieces of orbital debris using various technologies. Current efforts are focused on the development and demonstration of ADR technologies by both governmental space agencies and private companies. Proposed methods include robotic arms, nets, harpoons, laser systems, and drag augmentation devices designed to capture and deorbit large debris objects. However, the practical implementation of ADR policies faces several significant challenges. First, ADR technologies are inherently dual-use; systems such as lasers, harpoons, and nets can also be perceived as potential weapons, raising concerns about their possible use for hostile purposes and increasing geopolitical tensions. Second, ADR efforts are costly and may require considerable time to achieve meaningful reductions in orbital debris. Lastly, given that outer space is a global commons, an effective mechanism must be established to fairly contribute the costs of ADR among spacefaring nations and private actors.

Seminal studies on the economic implications of orbital debris include Adilov, Alexander, and Cunningham (2015, 2018), Macauley (2015), and Rouillon (2020), among others. For a comprehensive review of the literature, see Bongers et al. (2024). The specific implications of active debris removal (ADR) policies have been explored in works by Klima et al. (2016), Grzelka and Wagner (2019), Adilov et al. (2020), Guyot and Rouillon (2022), Bernhard et al. (2023), and Bongers et al. (2025). Klima et al. (2016) employ a game-theoretic framework in which spacefaring entities can choose to invest in costly ADR efforts that benefit all actors, or instead wait for others to take action, a classic free-rider problem. Grzelka and Wagner (2019) develop a model that incorporates property rights and policy instruments to incentivize ex ante improvements in satellite quality, as well as collective or individual debris take-back initiatives. Guyot and Rouillon (2022) analyze a setting where satellite operators determine satellite design choices, while in-orbit servicing firms provide debris removal services. Bernhard et al. (2023) apply a dynamic game model to assess the impact of satellite mega-constellations on debris generation and evaluate various taxation schemes to finance ADR policies. Finally, Bongers et al. (2025) construct a dynamic stochastic general equilibrium (DSGE) model to examine optimal ADR strategies and the design of satellite taxes to fund these interventions.

This paper contributes to the literature by introducing an IAM for the global economy and space environment, designed to inform the development of optimal active debris removal (ADR) policies. In the environmental economics literature, IAMs have a long-standing tradition of being used to assess the costs of carbon emissions and to guide design optimal climate policy. Building on this tradition, the model presented here extends the DISE-2024 framework developed in Bongers and Torres (2025) by incorporating abatement functions tailored to each type of debris. Like other IAMs, DISE-2024 consists of two interconnected components: an economic model and a physical model, while the economic component provides insights into optimal decision-making by agents whose actions affect human activity in space. The physical component captures the impact of economic activity on the space environment. These two sub-models are linked via a damage function. The economic module is based on the neoclassical optimal growth model, following the Ramsey (1928) framework, and is applied globally, encompassing both Earth and outer space. Social welfare is maximized through optimal choices regarding investment and abatement. The central planner makes two investment decisions and three ADR intervention decisions to internalize the externalities associated with space debris. Output is a function of labor (population) and two types of capital: Earth capital and space capital. Earth capital refers to traditional physical assets (equipment and structures), while space capital includes orbital assets, such as satellites. The model incorporates three exogenous sources of growth: aggregate neutral technological progress, investment-specific technological progress in satellites, and population dynamics. Abatement costs are associated with ADR policies aimed at reducing the social costs imposed by orbital debris. The physical model captures the dynamics of debris accumulation as a function of economic activity and endogenously debris generated debris. We differentiate between three types of debris: derelict satellites, rocket bodies, and fragments. This distinction is important for two reasons. First, the cost-effectiveness of mitigation policies varies across debris types, depending on the relative cost and benefit of removing each category. Second, while fragments are inert, derelict satellites and rocket bodies are susceptible to breakups and collisions, which can generate additional fragments and intensify the debris problem.

The calibrated model is numerically solved as a nonlinear programming problem for a simulation horizon of 200 years. We compare results from the optimal ADR policies with a scenario in which no ADR policies are implemented. The model produces optimal trajectories for economic variables such as per capita consumption, output, Earth capital investment, space capital investment, fraction of debris removed from orbit. It also generates outcomes for physical variables as the quantity of debris, number of satellites in orbit, and collisions. From these results, we estimate the probability of collision as a measure of the likelihood of the Kessler syndrome. The simulations yield four main findings. First, as economic activity increases, so does human activity is the space, leading to an increase in both the number of satellites and the accumulation of orbital debris. However, in the absence of ADR policies, we identify a tipping point for the number of operational satellites in orbit once the population of orbital debris reaches a threshold. In contrast, under optimal ADR policies, the number of operational satellites continues to rise, as the debris population remains under control, the probability of collision stays low, and the number of operational satellites lost to collision remains small. Second, optimal ADR policies are primarily focused on the removal of fragments. We find that the percentage of intact objects, both derelict satellites and rocket bodies, removed is very low compared to the fraction of fragments removed. This is partly due to the differing levels of potential damage each type of debris can inflict. Third, based on the calibration of the cost function using estimates from Colvin et al. (2023), the optimal fraction of world GDP to be devoted to space cleaning through debris removal is relatively small. This finding is also justified by the minor contribution of the space economy to the global economy. Finally, we find that the probability of collisions remains very low values when optimal ADR policies are implemented, and the risk of a Kessler syndrome can be ruled-out.

The remainder of the paper is organized as follows. In Section 2, a global economy-space model is developed to illustrate the relationship between final output and the number of satellites in a space environment affected by orbital debris. In Section 3, the model's solution is presented for a centralized economy, in which a central planner chooses the optimal level of abatement through an ADR policy. The model is parameterized and calibrated in Section 4. Section 5 presents a summary of the simulation results and compares the outcomes of optimal ADR policies with those of an economy in which no ADR policies are implemented. Finally, Section 6 offers concluding remarks.

2. THE DYNAMIC INTEGRATED SPACE ECONOMY (DISE-ADR) MODEL

This section describes the structure of the DISE-ADR model. The model is an extension of the DISE-2024 model by Bongers and Torres (2025), enhanced by incorporating an abatement cost function for the implementation of ADR policies. The abatement policy is tailored to each type of debris, as the impact of their emissions varies, particularly because intact objects can breakup and generate a large number of fragments. The model considers three types of debris: derelict satellites, rocket bodies, and fragments. Given the specific characteristics of each type of debris (mass, size, etc.), the parameterization of the abatement cost function is unique for each category.

The economic part is represented by an optimal growth model for the world economy, comprising two capital inputs, in which "satellites" are treated as an additional form of capital in the aggregate production function. The model is based on the neoclassical dynamic general equilibrium growth framework. It incorporates a negative externality that arises from the pollution of outer space with orbital debris. Output is allocated among

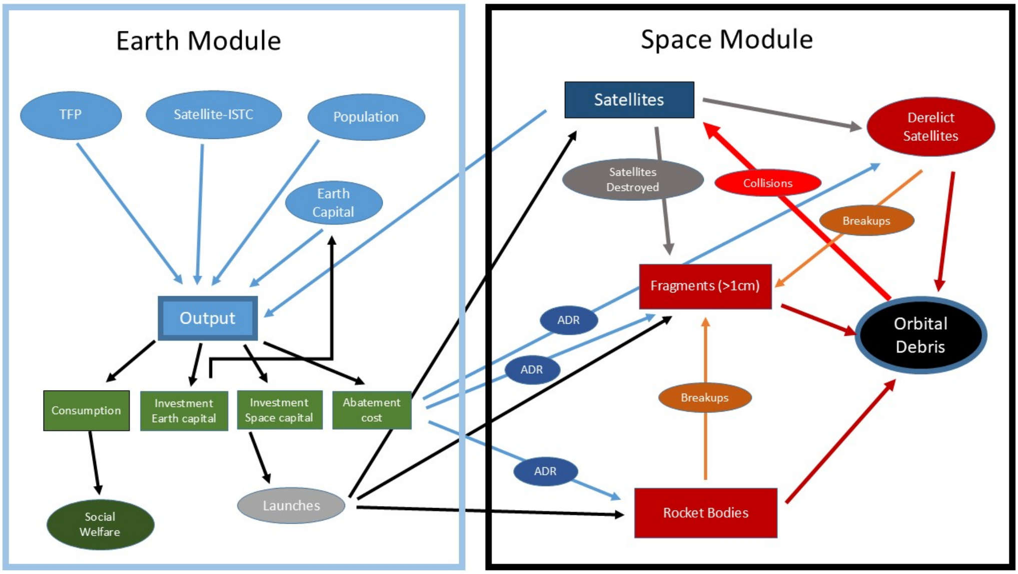

FIGURE 1. Scheme of the DISE-ARD model

This scheme shows the two modules of the DISE-ADR model. The Earth module represents an otherwise standard growth world economy with the sole different that satellites are an additional input in the production function and that an investment decision takes place to build-up space capital producing pollution in the space in the form of orbital debris. Final output is divided between consumption, investment in Earth capital, investment in space capital and abatement cost. Abatement cost reflects specific ADR policies for removing debris from orbit. Orbital debris produces damages in the form of collisions with satellites, which in turn reduces the stock of space capital.

consumption, investment in physical capital on Earth, investment in satellites, and abatement interventions. Unlike standard environmental economic models, pollution in this context does not directly reduce output by lowering aggregate productivity. Instead, the cost of orbital pollution stems from its effect on increasing the risk of collision and destruction of operational satellites. This, in turn, reduces the stock of in-orbit equipment, which indirectly decreases production if the destroyed satellites are not replaced or diverts resources alternative uses if they are. In addition, the externality can affect economic growth by influencing capital investment, both in the space and in the Earth, and by altering the future stock of capital.

The physical part of the model is represented by a tractable orbital debris evolution model. Like the economy model, the space model is global in scope, covering all orbital regions from Low Earth Orbit (LEO) to Geostationary Orbit (GEO). In addition to modeling the population of operational satellites (and other spacecraft, including two space-stations), the model captures the dynamics of orbital debris. The debris population considered includes objects larger than 1 cm in size and is categorized into three types: Derelict non-deorbited dead satellites, upper stages rocket bodies abandoned in orbit, and fragments. A key feature of the model is that both dead satellites and rocket bodies can breakup, generating additional fragments or can collide with other objects, thereby contributing to the growth of the debris population. Figure 1 shows the scheme of the model.

2.1 *The economy model*

The economy part of the model is based on the optimal neoclassical growth model of Ramsey (1928), adapted to account for human activity in space. Time is discrete and extends over an infinity horizon.

2.1.1 *Households* The economy is populated by a large number of identical households, represented by a single representative household with instantaneous utility $U(\hat{c}_t, N_t)$, defined over per capita consumption $\hat{c}_t$, and where N_t is population. The aggregate consumption, c_t, is defined as $c_t = \hat{c}_t N_t$. The function $U(\hat{c}_t, N_t)$ represents the flow of utility and assumed to reflect overall social welfare. The function $U(\cdot)$ is assumed to be concave and twice continuously differentiable.

The problem to be solved by the stand-in household consists in maximizing the sum of discounted utility,

$$max_{\{\hat{c}_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t U(\hat{c}_t, N_t) \tag{1}$$

where $\rho > 0$ is the subjective intertemporal preference parameter or the pure rate of social time preference. The discount factor, $0 < \beta < 1$, is defined as $\beta = 1/(1+\rho)$.

This household satisfies the following budget constraint which coincides with the feasibility constraint in the final-good sector:

$$c_t + i_t^k + i_t^s + o_t = y_t \tag{2}$$

where i_t^k is investment in physical capital other than satellites (Earth capital), i_t^s is investment in satellites (space capital), with includes all costs insert satellites into orbit, o_t is the abatement cost, and y_t is final output. Inserting a satellite into orbit requires the use of launch vehicle, which is costly. As a result, not all space investment spending is converted into productive space capital. All prices are defined in output units and are normalized to one, including the abatement cost. In this context, abatement cost reflects resources devoted to Active Debris Removal (ADR) policies. This is an ex-post policy aimed at reducing the existing stock of orbital debris, that is, cleaning the space from accumulated junk (i.e., negative debris emissions). ADR policies can be complemented by emissions mitigation policies strategies through the application of guidelines intended to minimize the creation of debris.

2.1.2 *Launch cost* To deploy a satellite capable of providing services, a launch vehicle must be used. Launch vehicles, typically by the use of multi-stage rockets, represent a significant share of the total cost of satellites deployment. To account for this, investment in space capital is divided into two components:

$$i_t^s = h_t + l_t \tag{3}$$

where h_t is the satellites hardware cost, and l_t is the launch cost. The launch cost is interpreted as an installation cost necessary to build up the satellites stock. The launch cost is modeled as a fixed adjustment cost per unit of investment, reflecting the fact that launch prices are typically fixed per kilogram of satellite mass, though they may vary depending on the target orbit. Alternatively, the launch cost can be viewed as a wedge or premium over the purchase price of space capital.

The installation cost function is defined as:

$$l_t = m_t i_t^s \tag{4}$$

where $0 < m_t < 1$ is the fraction of launch cost over the total investment cost in space capital. The installation cost is assumed to represent only a fraction of the total investment cost. In the macroeconomic literature, investment adjustment costs are commonly used to smooth capital accumulation and to replicate observed investment dynamics. These costs reflect the idea that adjusting the capital stock is not frictionless, that is, firms cannot install or reallocate capital instantly or without cost. Therefore, the fraction of investment in space capital that accumulates into operational satellites is defined as,

$$h_t = (1 - m_t) i_t^s \tag{5}$$

We assume that launch costs decrease over time at the rate $g_{m,t} < 0$, where,

$$m_{t+1} = exp(g_{m,t}) m_t \tag{6}$$

$$g_{m,t} = g_{m,0}(exp(-\delta_m t)) \tag{7}$$

where $g_{m,0} < 0$ and $\delta_m > 0$ is the decay in the growth rate of launch costs.

2.1.3 *Abatement* A fraction of income is allocated to abatement, not for the purpose to prevent emissions but to reduce the stock of pollution (negative debris emissions). In the environmental economic literature, abatement cost are typically interpreted as the cost of interventions aimed at reducing emissions to control environmental damage. In our framework, abatement cost refers specifically to the expenditures associated with Active Debris Removal (ADR) policies, that is, efforts to capture and remove orbital debris after its generation during space-related activities. Accordingly, we distinguish between passive and active debris mitigation policies. ADR represents an active policy approach, involving the deployment of technologies designed to remove debris from orbit, in a manner analogous to Carbon Dioxide Removal (CDR) technologies. For a review of the different technologies under investigation for ADR under development, see Mark and Kamath (2019).

Abatement cost is defined as,

$$o_t = \sum_j o_{j,t} \qquad for \;\; j = w, z, f \tag{8}$$

where $o_{w,t}$ is the abatement cost of removing derelict satellites, $o_{z,t}$ is the abatement cost of removing upper stages rocket bodies, and $o_{f,t}$ is the abatement cost of removing fragments. Following Nordhaus (2008), we assume that the abatement costs are proportional to global output. It is further assumed that the fraction of each type of debris removed each period, $b_{j,t}$, is a function of the fraction of output allocated to abatement,

$$o_{j,t} = g^{j}(b_{j,t})y_t \tag{9}$$

In this specification, the fraction of debris removed, $b_{j,t}$, is a function of the abatement spending, where the function $g^{j}(b_{j,t})$ relates the fraction of the type j debris removed to the ratio of abatement spending to output.

2.1.4 *The technology* We assume that all firms have access to the same technology; therefore, the analysis is conducted using a representative firm and a representative aggregate production function. Output is assumed to be a function of aggregate productivity, the stock of physical capital on the Earth, k_t, the stock of satellites, s_t, and labor, N_t,

$$y_t = a_t f(k_t, s_t, N_t) \tag{10}$$

where a_t is the Total Factor Productivity (TFP), representing Hicks-neutral technological change. Labor is assumed to be equal to population, and therefore, the growth rate of labor is equal to the population growth rate.

The accumulation of physical capital other than satellites follows the standard capital accumulation equation:

$$k_{t+1} = (1-\delta_k)k_t + i_t^k \tag{11}$$

where $0 < \delta_k < 1$ is the capital depreciation rate.

The stock of satellites, measured in final output units as an equipment asset, is denoted by s_t, and is given by the following process,

$$s_{t+1} = (1-\delta_s)s_t + q_t(i_t^s - l_t) - x_t \tag{12}$$

where $0 < \delta_s < 1$ is the depreciation rate for satellites, and x_t represents the loss of satellites assets due to collisions (damage from space pollution), which will defined later. This accumulation process establishes the link between the space environment and economic activity. Damage results in the destruction of satellites, the reduction of space capital stock used in production, and the reduction of the final output if the loss asset are not replaced. The stock of satellites law of motion incorporates an investment-specific technological change (ISTC), denoted by q_t, (see Greenwood et al., 1997). For simplicity, it is assumed that ISTC occurs only in the space sector.

2.1.5 *Exogenous growth sources* The model incorporates three exogenous sources of growth: aggregate neutral technological change, investment-specific technological change for satellites, and aggregate labor growth. The growth rates of technological change and population are not a constant; rather, similar to climate change AIMs, they are assumed to decline over time. Aggregate productivity technological progress is characterized as,

$$a_{t+1} = exp(g_{a,t})a_t \tag{13}$$

where $g_{a,t}$ is the growth rate of TFP defined as,

$$g_{a,t} = g_{a,0} exp(-\delta_a t) \tag{14}$$

where δ_a is the decay rate in the TFP growth rate.

We assume a similar specification for the satellite investment-specific technological progress,

$$q_{t+1} = exp(g_{q,t}) q_t \tag{15}$$

where $g_{q,t}$ is the growth rate of ISTC defined as,

$$g_{q,t} = g_{q,0} exp(-\delta_q t) \tag{16}$$

where δ_q is the decay rate in ISTC for satellites.

Finally, we define the dynamics of the population, N_t. Population represents another source of growth, as labor is assumed to equal population. Following the specification by Hassell (1975), population dynamics are defined as,

$$N_{t+1} = N_t \left(\frac{N^*}{N_t} \right)^{\varsigma} \tag{17}$$

where N^* is the asymptotic population at the end of the simulation period and ς is a population growth parameter.

2.1.6 *Economic to physical variables mapping* To obtain a numerical solution of the model it is necessary to use different units of some variables. First, some variables need to be measured in monetary units, but simultaneously they need also be measured in physical units. A typical example is satellites. Satellites is an input in the aggregate production function and a result of the accumulation of investment in space capital. On the other hand, the number of satellites is the relevant variable for computing damages in the form of operational satellites destroyed by collision. Second, in the space model, the dynamics for debris is a function of physical variables such as the number of launches, which is also related to the resources spent in launches. In order to ensure that the model's parameters are calibrated correctly and that economic and physical variables are integrated properly, a mapping between the two environments must be established.

The first step in creating this mapping involves connecting the stock of satellites as a capital asset, s_t, expressed in output units, with the number of satellites, S_t, is given by,

$$S_t = \mu s_t \tag{18}$$

where the parameter μ the conversion parameter that transforms "economic" values into "physical" values. This parameter can be interpreted as the inverse of the price of a satellite. Notice that satellite's ISTC affects the productivity value of the asset but not the quantity of assets. ISTC is considered embodied technological progress in new vintages of satellites. The higher the value of q_t, the larger the number of new satellites produced per unit of investment. In practice, a positive trend in q_t reflects embodied technological change in spacecraft reflecting a decreasing trend in manufacturing costs of satellites.

Similarly the number of satellites destroyed by collisions, X_t, is defined as,

$$X_t = \mu x_t \tag{19}$$

A second mapping is assumed between the investment in satellites and the number of new satellites inserted into orbit, H_t,

$$H_t = \mu q_t (i_t^s - l_t) = \mu q_t h_t \tag{20}$$

where the number of new satellites is proportional to investment in space capital net of installation costs.

By substituting the above mappings into the restriction (12), we can derive the accumulation process for the number of satellites. Therefore, the stock of operational satellites, measured by the numbers of a representative satellites can be expressed as,

$$S_{t+1} = (1 - \delta_s) S_t + H_t - X_t \tag{21}$$

Satellites are equipment assets placed in orbit. Therefore, each period, the amount $\delta_s S_t$ of satellites becomes non-operational and is thus considered a type orbital debris (i.e., derelict satellites).[1] According to expression (21), the negative externality produced by orbital debris can be measured by the number of non-functioning satellite assets, or equivalently, expressed in terms of GDP (as in expression 12).

2.1.7 *Rockets launches* Launches is an instrumental variable in the economic part of the model (an installation cost) but plays a key role in the physical part. First, it is necessary to define the number of launches as an additional variable given that the primary source of debris emission is launch activity. Standard launch systems typically involve the use of rockets with several (three to four) stages. Some of these stages (parts of the launch vehicle, including fuel tanks and engines) remain in orbit one the payload has been inserted into orbit. Moreover, during the insertion phase, additional debris is generated from discarded components such as payload fairings. It is true that technological progress in launch systems has introduced reusable vehicles that do not produce debris. On the other hand, both public space agencies and private companies follow a set of guidelines to mitigate the creation of debris associated with launch operations. Second, the number of launches is not equal to the number of satellites inserted into orbit. Indeed, the number of satellites per launch has increased dramatically during the last decade. The availability of more powerful launch vehicles with higher payload capacity, together with the reduction in the size and weight of satellites, has increased the number of satellites per launch. Therefore, the number of satellites inserted into orbit, H_t, is assumed to be a proportion η of the number of launches, L_t:

$$H_t = \eta L_t \tag{22}$$

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[1] Satellites that are no longer useful remain in orbit and turn into space debris if not removed. Defunct satellites can be removed from orbit by raising their altitude to a graveyard orbit for geostationary satellites, or by decreasing their altitude to increase atmospheric drag for low and medium Earth orbit satellites, causing them to burn up in the Earth's atmosphere. Any large debris that survives re-entry is disposed of in the so-called spacecraft cemetery located in the Pacific Ocean, in an uninhabited area east of New Zealand.

where the parameter η can be interpreted as the number of satellites deployed per launch. Taking advantage of expression (22), and from the mapping between investment in satellites and the number of new satellites inserted into orbit (expression 20), we can obtain the relationship between investment in satellites net of installation costs, and the number of launches, given by,

$$h_t = \frac{\eta}{\mu q_t} L_t \tag{23}$$

2.2 *The space model*

Next, we describe the physical space model. This part of the model includes three main functions: the damage function, the emission (debris generation) function, and the low of motion of the stock of debris. Any human-made object that is not functional and is orbiting around Earth is considered space junk, which moves at high speeds and has the potential to collide with and destroy other objects. We distinguish three types of orbital debris: Derelict satellites, rocket bodies, and fragments.

2.2.1 *The stock of pollution* Pollution in Earth's orbit takes the form of orbital debris. The stock of orbital debris includes any non-operative, human-created object in orbit, that is, it excludes functioning satellites and other spacecraft. We measure orbital debris by counting the number of objects. The stock of debris, D_t can be defined as:

$$D_t = W_t + Z_t + F_t \tag{24}$$

where W_t is the stock of derelict satellites abandoned in orbit, Z_t is the number of final-stage rocket bodies, and F_t are fragments larger than 1 cm. The key distinction is that fragments are dead debris, where both derelict satellites and rocket bodies can breakup generating a large number of fragments.

2.2.2 *Damages* Human activities in outer space produce pollution in the form of orbital debris, which travels at high speeds (on average of 36,000 km/h, or approximately 10 kilometer per second in LEO). This debris can collide with operational satellites and other spacecraft, leading to the loss of valuable space assets. While it is true that some uncontrolled, large mass debris in low orbit can re-enter the Earth's atmosphere and potentially cause harm to life or property, the probability of such an event is very low.

Following Farinella and Cordelli (1991), the number of satellites destroyed each period due to collision with debris is modeled as a function of both the stock of debris and the number of operational satellites,

$$X_t = (1 - v_t)\theta D_t S_t \tag{25}$$

where $\theta > 0$ is a parameter representing the collision probability per unit of debris, v_t represents the collision avoidance capability of satellites, and D_t is the number of orbital debris. The probability of collision can be reduced through the use collision avoidance systems, which rely on tracking data and maneuver capabilities to prevent high-risk encounters. Notice that, given the above expression, satellite assets destroyed by collision,

x_t, is defined as,

$$x_t = (1 - v_t)\theta D_t s_t \tag{26}$$

given that $X_t = \mu x_t$ and $S_t = \mu s_t$. Adilov et al (2018) defines the "Kessler syndrome" as a situation in which the probability of collision is one, $(1 - v_t)\theta D_t = 1$, any space assets are destroyed, rendering the orbital environment unusable. This critical threshold is reached when the pollution stock reaches $D_t = 1/\theta(1 - v_t)$.

2.2.3 *Debris generation* Debris comes from different sources: launches (including derelict final-stage rockets and fuel deposit bodies), derelict satellites not removed from orbit, accidental explosions and breakups, collisions, and intentional debris creation through military activities, such as destroying a satellite using an anti-satellite missile. The integrated model identifies the following five sources of orbital debris:

The first source of debris is Mission Related Objects (MRO). This source of debris is directly related to the number of launches. We assume that this debris generation process is represented by ωL_t, where ω is the number of debris items creates per launch at the time of the launch. This type of debris are classified as "fragments" and includes protection fairing, covers, adapters, bolts, cables, etc. Second, launches also produce another type of debris as usually final stages of launch vehicles that often remain in orbit after payload insertion. Rocket bodies are large-size debris with a significant risk of breakup. We assume that the number of rocket bodies produced per launch is given by φL_t, where $0 < \varphi < 1$ represents the fraction of launches that produce this type of debris. We assume that this fraction is strictly less than one in account for the existence of reusable launch vehicles. This type of debris will accumulate into a stock of rocket bodies in orbit. The third source of debris are derelict satellites, W_t. Derelict satellites are end-of-live satellites that are no longer operational (generally due to fuel depletion) and are not de-orbited and instead abandoned in orbit. In each period, the number of end-live satellites is $\delta_s S_t$. Each period, a fraction χ of end-live satellites are abandoned in orbit. The fourth source of debris generation is fragmentation events due to explosions and breakup of both derelict satellites and rocket bodies. These fragmentation events can be unintentional or deliberate. Unintentional fragmentation debris originates from the breakup of operational satellites, body rockets or engines. The primary cause of in-orbit explosions is related to residual fuel remaining in the tanks of rockets' upper stages and satellites. The extreme conditions in outer space cause mechanisms and devices to deteriorate rapidly, leading to leaks mixing fuel components, which provoke accidental explosions that break-up rocket bodies and other spacecraft. Batteries can also explode. Orbit explosions are mainly caused by residual fuel in tanks or fuel lines once a rocket stage or satellite sinks into Earth's orbit. The harsh space environment can gradually damage the mechanical integrity of external and internal parts, leading to leaks and/or mixing of fuel components, which could trigger self-ignition. As a result, the explosion can destroy the source object and scatter its mass across numerous fragments with varying masses and velocities.[2] The last source of

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[2] In addition, spacecraft interceptions by surface-launched missiles have become a significant source of debris in recent years. For instance, the intentional destruction of the Chinese Feng-Yun 1C satellite by a missile in January 2007 alone increased the trackable space object population by approximately 30% (OECD,

debris generation is fragmentation due to collision between objects. The model accounts for Collisions between operational satellites and debris, and collision of derelict satellites, and rocket bodies with each other and with fragments. Taking into account the sources of debris emissions, we next define the law of motion for the three types of de debris.

2.2.4 *Derelict satellites* The law of motion of derelict satellites is given by,

$$W_{t+1} = (1 - \delta_w - \varepsilon_w - b_{w,t})W_t - \theta(D_t + (1 - v_t)S_t)W_t + \chi\delta_s S_t \tag{27}$$

where δ_w is the natural decay rate of derelict satellites, and ε_w is the fraction of derelict satellites that explode in each period. The natural decay rate of debris varies significantly with altitude. At low altitudes, this ratio is very high, leading to short lifespan for debris. However, as altitude increases, the natural decay rate declines exponentially. At high altitudes, it approaches zero. The fraction of derelict satellites removed through abatement efforts (ADR interventions) is given by $b_{w,t}$. This fraction depends on the cost of de-orbiting this specific type of debris. The dynamics of the stock of abandoned end-life satellites into orbit will also depend on the regulatory policies governing end-mission disposal. For example, a mandatory de-orbiting policy for non-operational spacecraft would imply that $\chi = 0$, and therefore, the stock W_t would tend toward zero over time, due to both natural decay and explosions. In case of explosions, the number of debris fragments generated is $\phi_w \varepsilon_w W_t$, where ϕ_w is the number of fragments per exploding derelict satellite. The term $\theta(D_t + (1 - v_t)S_t)W_t$ represents the number of derelict satellites fragmented by collisions.

2.2.5 *Rocket bodies* Second, the stock of body rockets can be defined as

$$Z_{t+1} = (1 - \delta_z - \varepsilon_z - b_{z,t})Z_t - \theta(D_t + (1 - v_t)S_t)Z_t + \varphi L_t \tag{28}$$

where δ_z is the natural decay rate of body rockets bodies, ε_z is the fraction of body rockets that breakup each period, and $b_{z,t}$ is the fraction of rocket bodies removed from orbit by ADR interventions. The number of debris fragments produced by the breakup of a large rocket body is given by $\phi_z \varepsilon_z Z_t$. The term $\theta(D_t + (1 - v_t)S_t)Z_t$ represents the number of rocket bodies fragmented by collisions.

2.2.6 *Fragments* The third type of debris considered are fragments. The stock of fragments increases due to the following sources: debris from launches (mission-related objects), breakups of derelict satellites and body rockets, collisions between debris and operational satellites, and intentional military anti-satellite tests. We consider only collisions between operational satellites with debris; collision between debris themselves are not considered. Formally, the law of motion of fragments is given by,

$$\begin{aligned} F_{t+1} = {} & (1 - \delta_f - b_{f,t})F_t + (1+\Gamma)\omega L_t + (1+\Gamma)\gamma_s X_t + (1+\Gamma)\phi_w \varepsilon_w \theta W_t \\ & + (1+\Gamma)\phi_z \varepsilon_z Z_t + (1+\Gamma)\gamma_w \theta D_t W_t + (1+\Gamma)\gamma_z \theta D_t Z_t \end{aligned} \tag{29}$$

2020). Rocket bodies are also a contributing factor to fragmentation events. Besides such accidental break-ups, spacecraft interceptions by surface-launched missiles have been a major contributor in the recent past. Four countries, the US, Russia, China and India have conducted direct-ascend anti-satellite tests. A single event, the intentional destruction of the Chinese Feng-Yun 1C satellite by a missile in January 2007, increased the trackable space debris population by 30% (OECD, 2020).

where δ_f is the natural decay of fragments, $b_{f,t}$ is the fraction of fragments removed from orbit through ADR interventions, γ_s is the number of tracked debris fragments created by a collision that destroys an operational satellite, and ω is the number of tracked fragments produced per launch. We exclude the possibility that operational satellites can breakup due to design failure. The number of tracked fragments produced by the collisions of derelict satellites with other debris is denoted by γ_w, and γ_z represents the number of tracked fragments produced by the collision of rocket bodies with other debris. The parameter Γ is a scaling factor that converts the number of fragments larger than 10 cm into fragments larger than 1 cm.

3. THE SOCIAL PLANNING PROBLEM

This section states the planning problem to derive the optimal allocation of resources under ex-post abatement policies, taking into account how the accumulation of orbital debris affects the economy and vice-versa. In this case, we assume that ADR technology is available, and that the central planner chooses the optimal fraction of resources to be allocated to removing orbital debris from orbit.

The central planner chooses consumption, investment in capital, investment in satellites (launches), and abatement of derelict satellites, rockets bodies, and fragments, to maximize social welfare. The social planner maximizes (1) subject to (2), (3), (4), (5), (6), (7), (10), (22), (23), (24), (25), and (27), using (16), (17), (18), and (20) as auxiliary restrictions. Formally, the maximization problem can be defined as:

$$\mathcal{L} = E_t \sum_{t=0}^{\infty} \beta^t U(\hat{c}_t) N_t \quad (30)$$

$$- \sum_{t=0}^{\infty} \lambda_{1,t} \left[c_t + k_{t+1} - (1-\delta_k)k_t + \frac{\eta}{\mu q_t (1-m_t)} L_t - \left(1 - \sum_j g^j(b_{j,t})\right) a_t f(k_t, s_t) \right]$$

$$- \sum_{t=0}^{\infty} \lambda_{2,t} \left[x_t - (1-v_t)\theta D_t s_t \right]$$

$$- \sum_{t=0}^{\infty} \lambda_{3,t} \left[s_{t+1} - (1-\delta_s)s_t - \frac{\eta}{\mu} L_t + x_t \right]$$

$$- \sum_{t=0}^{\infty} \lambda_{4,t} \left[D_t - W_t - Z_t - F_t \right]$$

$$- \sum_{t=0}^{\infty} \lambda_{5,t} [W_{t+1} - (1-\delta_w - \varepsilon_w - b_{w,t})W_t + \theta(D_t + (1-v_t)S_t)W_t - \chi \delta_s S_t]$$

$$- \sum_{t=0}^{\infty} \lambda_{6,t} [Z_{t+1} - (1-\delta_z - \varepsilon_z - b_{z,t})Z_t + \theta(D_t + (1-v_t)S_t)Z_t - \varphi L_t]$$

$$- \sum_{t=0}^{\infty} \lambda_{7,t} [F_{t+1} - (1-\delta_f - b_{f,t})F_t - (1+\Gamma)\omega L_t - (1+\Gamma)\gamma_s X_t$$

$$- (1+\Gamma)\phi_w \varepsilon_w W_t - (1+\Gamma)\phi_z \varepsilon_z Z_t - (1+\Gamma)\gamma_w \theta D_t W_t - (1+\Gamma)\gamma_z \theta D_t Z_t]$$

The Lagrangian multipliers for each constraint in period t are $\lambda_{1,t}$, $\lambda_{2,t}$, $\lambda_{3,t}$, $\lambda_{4,t}$, $\lambda_{5,t}$, $\lambda_{6,t}$, and $\lambda_{7,t}$. $\lambda_{1,t}$ is the standard shadow price of consumption, $\lambda_{2,t}$ is the cost of the probability of collision, $\lambda_{3,t}$ is the shadow price of satellite assets, and $\lambda_{4,t}$ is the shadow cost of the stock of orbital debris, and where the individual shadow cost for derelict satellites, rocket bodies, and fragments, are given by the Lagrangian multipliers $\lambda_{5,t}$, $\lambda_{6,t}$, and $\lambda_{7,t}$, respectively.

From the maximization problem we obtain the following first-order conditions for $t = 0, 1, 2, ..., \infty$,

$$\beta^t U'(c_t) - \lambda_{1,t} = 0 \tag{31}$$

$$\begin{aligned} -\lambda_{1,t} + \lambda_{1,t+1}[(1-\delta_k) \\ +(1 - g^w(b_{w,t+1}) - g^z(b_{z,t+1}) - g^f(b_{f,t+1}))a_{t+1}f'_k(k_{t+1}, s_{t+1})] = 0 \end{aligned} \tag{32}$$

$$\begin{aligned} \lambda_{1,t+1}[(1 - g^w(b_{w,t+1}) - g^z(b_{2,t+1}) - g^f(g_{f,t+1}))a_{t+1}f'_s(k_{t+1}, s_{t+1})] \\ +\lambda_{2,t}(1-v_t)\theta D_{t+1} - \lambda_{3,t} + \lambda_{3,t+1}(1-\delta_s) \\ -\lambda_{5,t+1}(\theta(1-v_t)\mu W_{t+1} - \chi\delta_s\mu) - \lambda_{6,t+1}(\theta(1-v_{t+1})\mu Z_{t+1}) = 0 \end{aligned} \tag{33}$$

$$-\lambda_{1,t}\frac{\eta}{\mu q_t(1-m_t)} + \lambda_{3,t}\frac{\eta}{\mu} + \lambda_{6,t}\varphi + \lambda_{7,t}(1+\Gamma)\omega = 0 \tag{34}$$

$$\lambda_{2,t}(1-v_t)\theta s_t - \lambda_{4,t} - \lambda_{5,t}\theta W_t - \lambda_{6,t}\theta Z_t + \lambda_{7,t}(1+\Gamma)[\gamma_w\theta W_t + \gamma_Z\theta Z_t] = 0 \tag{35}$$

$$-\lambda_{2,t} - \lambda_{3,t} + \lambda_{7,t}(1+\Gamma)\gamma_s\mu = 0 \tag{36}$$

$$\begin{aligned} \lambda_{4,t+1} - \lambda_{5,t} + \lambda_{5,t+1}(1-\delta_w-\varepsilon_w-b_{w,t+1}) - \theta(D_{t+1} + (1-v_t)\mu s_{t+1}) \\ +\lambda_{7,t+1}(1+\Gamma)[\phi_w\varepsilon_w + \gamma_w\theta D_{t+1}] = 0 \end{aligned} \tag{37}$$

$$\begin{aligned} \lambda_{4,t+1} - \lambda_{6,t} + \lambda_{6,t+1}(1-\delta_z-\varepsilon_z-b_{z,t+1}) - \theta(D_{t+1} + (1-v_t)\mu s_{t+1}) \\ +\lambda_{7,t+1}(1+\Gamma)[\phi_z\varepsilon_z + \gamma_z\theta D_{t+1}] = 0 \end{aligned} \tag{38}$$

$$+\lambda_{4,t+1} - \lambda_{7,t} + \lambda_{7,t+1}(1-\delta_f-b_{f,t+1}) = 0 \tag{39}$$

4. FUNCTIONAL SPECIFICATION, INITIAL DATA, AND CALIBRATION

The model economy is intended to represent the global economy, also reflecting the global commons nature of outer space. That is, outer space is treated as a shared resource affected by the actions of all spacefaring nations and firms, making coordinated policy responses essential for the implementation of abatement policies. Economic variables refer to the world economy. Space variables represent all Earth's orbits.

4.1 *Functional specification*

In the model, there is no uncertainty. There is a continuum of identical households, each of whom has preference that are characterized by the following constant relative risk-aversion (CRRA-type) utility function,

$$U(\hat{c}_t) = \left(\frac{\hat{c}_t^{1-\sigma} - 1}{1-\sigma}\right) \tag{40}$$

where $\sigma \geq 0$ is the relative risk aversion parameter. The parameter σ can also be interpreted as a measure of social aversion to changes in consumption (Nordhaus, 1993).

It is assumed that the production function is of Cobb-Douglas type, exhibiting constant returns to scale, where labor equals population,

$$y_t = a_t k_t^{\alpha_1} s_t^{\alpha_2} N_t^{1-\alpha_1-\alpha_2} \tag{41}$$

where $0 < \alpha_1, \alpha_2 < 1$.

The abatement function is defined as the proportion of debris removed as a function of the abatement cost relative to output. Following Nordhaus (2008), it is assumed that the cost function for debris removal is convex, reflecting increasing marginal cost. Nordhaus (2008) assumes that the abatement costs are proportional to global output and to a power function of the abatement rate. We use a similar abatement specification but specific to each type of debris, such as:

$$\begin{aligned} o_{w,t} &= \nu_1 b_{w,t}^{\nu_2} y_t \\ o_{z,t} &= \nu_3 b_{z,t}^{\nu_4} y_t \\ o_{f,t} &= \nu_5 b_{f,t}^{\nu_6} y_t \end{aligned} \tag{42}$$

where $b_{j,t}$ is the fraction of removed debris from type $j = w, z, f$, and ν_1, ν_3, and ν_5 are proportional parameters representing the cost of removing a piece of debris of each type. The parameters ν_2, ν_4, and ν_6 determine the convexity of the abatement cost.

4.2 *Initial data and calibration*

Initial data corresponds to the year 2023. Both the initial values and the calibration of the model parameters, excluding the abatement cost parameters, are based on those used in DISE-2024. For a detailed description of the initial data and calibration of both economic and space parameters, see Bongers and Torres (2025). Table 1 summarizes initial values, while Table 2 presents the calibrated parameters of the model.

4.3 *Calibration of the abatement cost functions*

The abatement cost function follows the same specification as that used by Nordhaus (2008) and Heutel (2012). Nordhaus (2008) calibrates the exponent of the cost function to 2.8, reflecting a convex relationship between abatement efforts and cost. In addition, the coefficient multiplying the abatement fraction is assumed to be time-varying. Heutel (2012,) uses an initial value of 0.05607 for the year 2005, which declines gradually 0.0392 over a 50 years horizon, capturing the effects of technological progress or increasing efficiency in abatement.

For the calibration of the parameters of the abatement cost functions we use estimation costs of removing objects from orbit from a NASA technical report elaborated by Colving et al. (2023). Colvin et al. (2023) conduct a cost-benefit analysis of Active Debris Remediation (ADR) for both large intact debris and fragments. For large debris (derelict satellites

TABLE 1. Initial values for the year 2023

Variable	Value	Units	Source
World GDP	184.65	Trillions international US$	World Bank
Earth Capital stock	553.23	Trillions international US$	IMF and BEA
Space capital stock	1.72	Trillions international US$	IMF and BEA
Fraction of launch cost	0.30	Percentage	Adilov et al. (2022)
World Population	8,056	Millions inhabitants	United Nations
Operational satellites	8,500	Units	ESA
Number of launches	217	Units	NASA
Derelict satellites	3,524	Units	Model simulation
Rocket bodies	2,050	Units	NASA
Orbital debris > 10 cm	36,500	Units	NASA/ESA
Orbital debris > 1 cm	1,036,500	Units	NASA/ESA

and rocket bodies) remediation, they evaluate the removal of the 50 statistically most hazardous in LEO (Low Earth Orbit), as identified by McKnight et al. (2021). They estimate an initial benefit of \$3.5 million in the first year following removal, with cumulative benefit reaching \$1,100 million over 25 years. The estimated cost of removal is approximately \$800 million for uncontrolled reentry and over \$1 billion for controlled reentry. For small debris remediation, they estimate the benefit of removing 100,000 pieces of 1–10 cm debris from altitudes of 450–850 km. The expected reduction in risk is valued at \$23 million, with an accumulated benefit of around \$7.5 billion over 25 years, at an estimated cost between \$30 and \$600 million using ground-based lasers. This implies that the cost of removing a single piece of debris ranges from \$300 to \$6,000.

For the calibration of the parameters of the abatement functions We proceed as follows. First, following Nordhaus (2008), we assume that abatement cost functions are convex. In particular, we assume quadratic abatement cost functions, implying that the exponents in the abatement functions are set to $\nu_2 = \nu_4 = \nu_6 = 2$. Second, we assume that the cost of removing a derelict satellite is equal to the cost of removing a rocket body, and hence, we set ($\nu_1 = \nu_3$). To calibrate the abatement cost coefficient for large debris, according to Colvin et al. (2023), the cost of removing 50 high-risk large objects, including both derelict satellites and rocket bodies, is approximately \$1 billion. These 50 objects represent approximately 0.9% of the total population of large debris, given by the sum of 3,500 derelict satellites and 2,050 rocket bodies, i.e.,

$$\nu_1 = \nu_3 = \frac{o_{w,t}}{b_{w,t}^2 y_t} = \frac{1 \times 10^9}{8.1 \times 10^{-5} \times 184.65 \times 10^{12}} = 0.0667 \tag{43}$$

For the case of fragments, we consider that removing 100,000 pieces of fragments between 1 and 10 cm implies an average cost of \$300 million. Given a population of debris between 1 and 10 cm of 1 million, this represents a 10% of the total population. Hence, we calculate,

$$\nu_5 = \frac{o_{f,0}}{b_{f,0}^2 y_0} = \frac{300 \times 10^6}{0.01 \times 184.65 \times 10^{12}} = 1.6247 \times 10^{-4} \tag{44}$$

TABLE 2. Baseline calibration of the parameters of DISE-2024

	Parameter	Definition	Value	Source
Economy	ρ	Pure preferences parameter	0.015	Nordhaus (2008)
	σ	Risk aversion parameter	1.500	Nordhaus (2008)
	α_1	Capital share	0.3479	BEA
	α_2	Satellite share	0.0021	BEA
	δ_k	Capital depreciation rate	0.07	Standard
	δ_s	Satellite depreciation rate	0.15	NASA
	g_a	TFP growth rate	0.015	Assumption
	g_q	Satellite ISTC growth rate	0.030	Assumption
	δ_a	TFP growth decay rate	0.001	Assumption
	δ_q	ISTC growth decay rate	0.005	Assumption
	ς	Population growth parameter	0.05	United Nations
	μ	Conversion parameter	4,942	Internal
Space	η	Satellites per launch	13.6	NASA
	θ	Collision risk parameter	1.25×10^{-10}	ESA
	χ	Fraction of abandoned satellites	0.40	ESA
	δ_f	Fragment natural decay rate	0.01	NASA
	δ_w	Derelict satellites natural decay rate	0.00015	Lafleur (2011)
	δ_z	Rocket bodies natural decay rate	0.00015	Lafleur (2011)
	ε_w	Fraction of dead satellites breakups	0.0012	NASA
	ε_z	Fraction of body rocket breakups	0.0012	ESA
	φ	Body rockets per launch	0.60	ESA
	ω	Fragments > 10 cm per launch	4	ESA
	ϕ_w	Fragments > 10 cm per derelict satellite breakup	44.6	ESA
	ϕ_z	Fragments > 10 cm per rocket body breakup	100.2	NASA/ESA
	γ_s	Fragments > 10 cm per operational satellite collision	70	NASA/ESA
	γ_w	Fragments > 10 cm per derelict satellite collision	70	NASA/ESA
	γ_z	Fragments > 10 cm per rocket body collision	70	NASA/ESA
	Γ	Proportion parameter fragments 10 cm to 1 cm	33.4	ESA

5. SIMULATION RESULTS

This section presents the main results for two alternative scenarios: No ADR intervention and optimal ADR policy. In both scenarios we consider a central planner that maximizes social welfare. To obtain numerical simulation, the model is reformulated as a non-linear programming (NLP) problem. The simulation covers the period 2024 to 2223, providing a 200 years time horizon with annual frequency. The model is implemented and solved using MATLAB in combination with the CasADi framework for algorithmic differentiation and numerical optimization (Andersson et al., 2019).

We begin by simulating the model under the no-ADR policy scenario. In this case, the central planner fully internalizes the negative externality represented by debris without employing any direct debris removal policies by choosing the optimal investment rates as a function of the accumulation of debris. This scenario remains highly plausible over the long term for several reasons. First, while various debris removal technologies exist, all are currently at different stages of experimental development and none have been widely deployed operationally. It is also important to highlight that most of these technologies

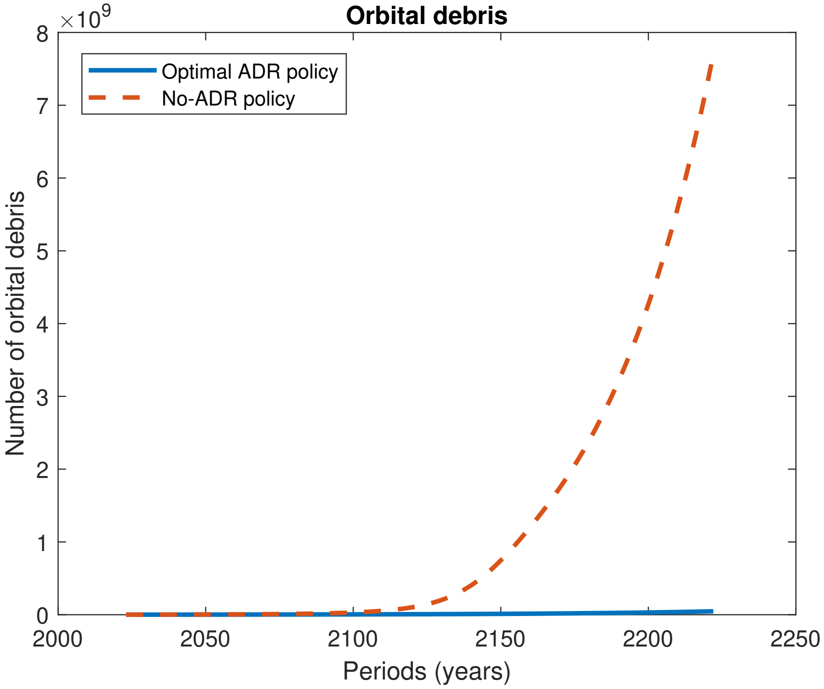

FIGURE 2. Orbital debris (larger than 1 cm)

This figure plots the trajectories of the population of orbital debris larger than 1 cm under the scenario of no-ADR and ADR policies. Whereas without ADR policies the accumulation of debris shows the typical exponential trend as predicted by the Kessler syndrome, with the optimal ADR policies the population of orbital debris remains under control for all the simulation horizon.

are only suitable for low Earth orbit (LEO), limiting their scope. Second, the question of who will bear the costs of debris removal remains unresolved. Because orbital debris constitutes a global externality, the benefits of debris mitigation are shared globally, but the associated costs are substantial and would likely fall on individual actors, creating significant incentives for free-riding. Since there are no property rights governing most orbital debris, except for ownership of functional spacecraft, no individual nation or firm has sufficient incentive to undertake costly removal efforts alone. Third, many ADR technologies are dual-use, meaning they can be repurposed as offensive space weapons. Techniques such as laser beams, harpoons, nets, drag augmentation devices, soldier satellites, and robotic arms, while potentially effective for debris removal, may be perceived as hostile technologies by other countries.

In the second scenario, we consider a regime in which an ADR policy is in place. Under this regime, the social planner has an instrument that allows for the active management of the orbital debris stock. The central planner fully internalizes the social cost associated with space debris by optimally allocating resources toward its removal. In this framework, the cost of removing a derelict satellite is assumed to be the same as that of removing a rocket body, reflecting their similar characteristics in terms of mass and complexity. However, this cost is assumed to differ from the cost of removing smaller debris fragments, which typically require different technologies and intervention strategies.

Figure 2 plots the number of orbital debris larger than 1 cm for the two scenarios. During the first 100 years, the trajectories are largely indistinguishable due to the large final scale of the simulation horizon, which reveals significant differences between the two scenarios in the long-run. The series begin at an initial level of 1 million pieces of orbital debris larger than 1 cm, as estimated by ESA for the year 2023. Over a 200 year horizon, the quantity of debris is increases by a factor of 5,000 in the non-ADR scenario, based on the baseline calibration of the model. The optimal ADR scenario reveals a significantly different long-run trend. In this scenario, the accumulation of debris larger than one centimeter is greatly reduced, reaching a value of 4.7×10^7. This is in contrast with the no-ADR scenario, where debris accumulation becomes uncontrollable, potentially leading to the onset of the Kessler Syndrome. Notice that this trajectory of orbital debris in the non-ADR scenario is calculated under no ex-ante emission mitigation policy. However, as shown in Bongers and Torres (2025) most debris mitigation policies, such as deorbiting of derelict satellites and rocket bodies, or debris-free launch systems are not enough to limit the accumulation of orbital debris due to its endogenous generation process in orbit.

Figure 3 shows the optimal number of operational satellites in orbit. The increasing number of satellites is a function of output growth, but the trajectory is also affected by the population of orbital debris and the risk of collision. During the initial years of the horizon, the stock of satellites to Earth capital ratio increases given the ISTC to satellites. However, even with a positive ISTC, the increase in the probability of collision leads to a reduction in the space capital to Earth capital ratio. Indeed, as the number of satellites increases, and space pollution increases as well, optimal trajectories start to diverge across the two scenarios. However, starting around 2080, they begin to diverge noticeably. When analyzing the optimal number of satellites under the implementation of an optimal ADR system, it becomes evident that this number increases substantially. The trajectory corresponding to the no-ADR scenario lies at the bottom, with the number of satellites peaking around the year 2150. In this scenario, the absence of mitigation policies results in the highest levels of debris and associated damages, which, in turn, reduce investment in satellite deployment. Whereas the trajectory of operational satellites with ADR policy has no limit, the stock of operational satellites shows a tipping point if no ADR intervention takes place.

Figure 4 presents the optimal trajectories for satellite launches, derelict satellites, rocket bodies, and satellites destroyed by collisions, both with and without ADR policies. Under ADR implementation, the number of optimal launches exhibits an upward trend, consistent with the growth of output and capital accumulation. In this scenario, no upper bound is observed, as ADR interventions effectively preserve a relatively clean orbital environment, allowing for sustained increases in satellite deployment. In contrast, the absence of ADR measures results in a lower optimal number of satellite launches, reflecting a reduced demand for orbital capacity. Over time, the accumulation of space debris in this scenario gradually constrains the expansion of launch activity, leading to a deceleration in the growth of satellite deployments.

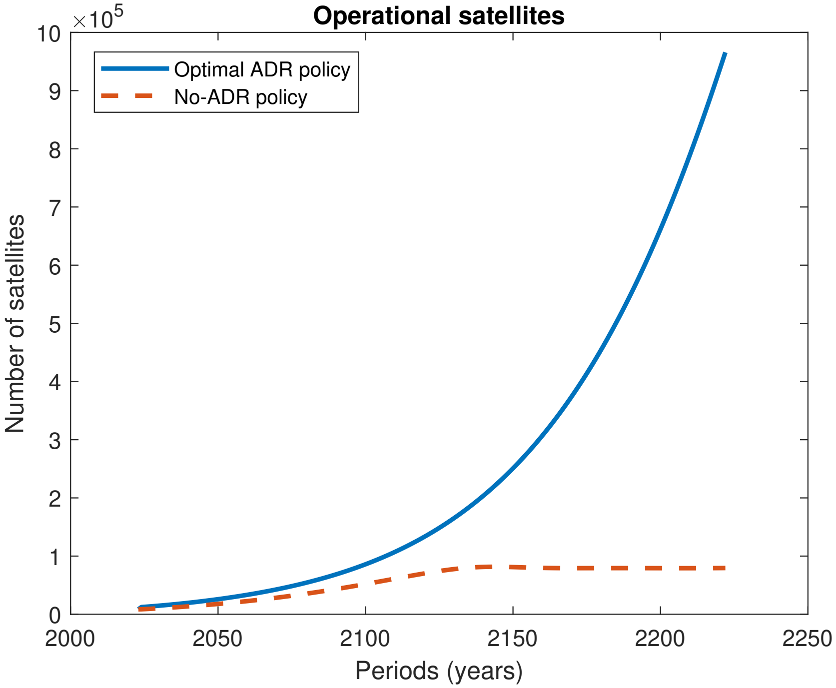

FIGURE 3. Optimal number of satellites in orbit

This figure plots the trajectories of the stock of operational satellites for the two scenarios. The implementation of ADR policies, by keeping an almost pollution free space environment, allows a positive trend in the accumulation of operational satellites in response to economic growth. No ADR interventions imply the existence of a limit for satellites.

Given the higher number of satellites and launches under the ADR policy scenario, the space environment contains more derelict satellites and rocket bodies compared to the scenario without ADR. In the absence of ADR interventions, the trajectories of derelict satellites and rocket bodies follow a hump-shaped pattern, as collisions gradually reduce the stock of large debris. The reduced launch activity in this scenario contributes to a lower accumulation of large objects, although it results in a significantly higher number of debris fragments due to increased collision rates. In contrast, with ADR policies in place, the number of debris fragments remains contained. However, the quantities of derelict satellites and rocket bodies grow exponentially, driven by intensified launch activity and a reduced rate of natural removal, as fewer objects are lost to collisions or reentry.

Finally, the number of operational satellites destroyed by collisions is substantially lower under ADR policies, as the population of fragment debris remains effectively controlled. In the absence of ADR interventions, satellite losses due to collisions follow a continuously increasing trajectory. By contrast, with ADR in place, the number of destroyed satellites remains significantly lower, reflecting the ability of such policies to sustain a relatively clean and stable orbital environment.

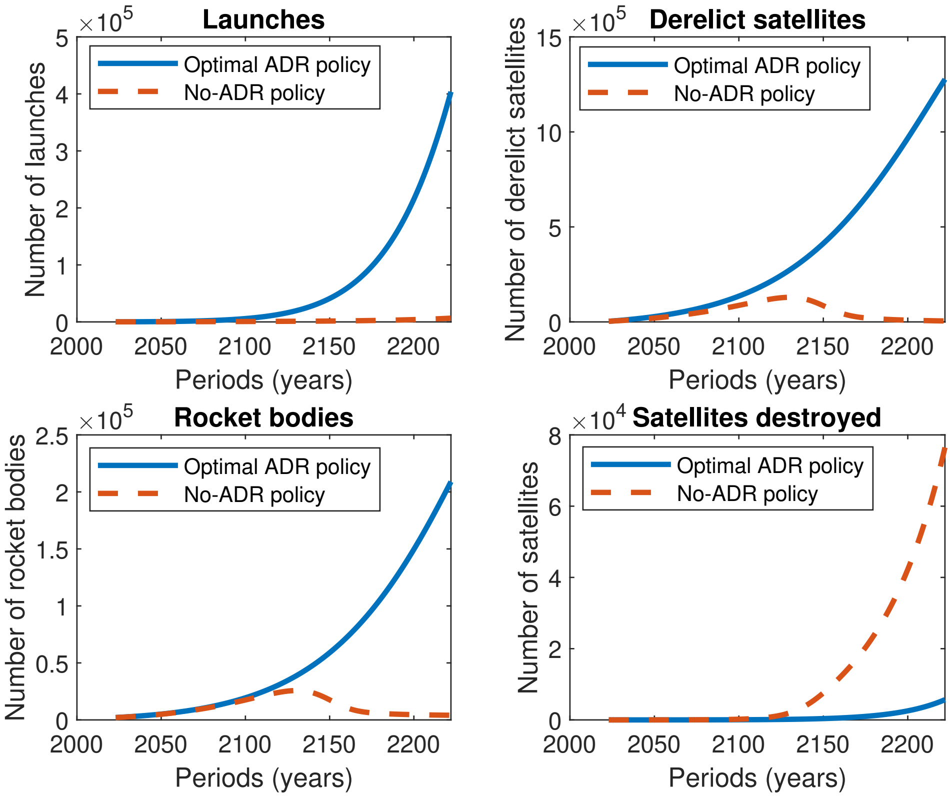

FIGURE 4. Launches, derelict satellites, rocket bodies, and operational satellites destroyed by collisions

This figure plots the number of launches, derelict satellites, rocket bodies, and number of satellites destroyed by collisions.

Figure 5 displays the optimal percentage of debris removed from orbit and the corresponding collision probability under both policy scenarios. The model indicates that optimal ADR efforts should focus more heavily on removing fragments rather than derelict satellites and rocket bodies. Specifically, the fraction of derelict satellites and rocket bodies removed remains relatively small, while the removal rate of fragments increases substantially, exceeding 80% by the end of the simulation period. This policy outcome is driven by two main factors. First, the relative cost of debris removal differs across object types. Based on the calibration of the abatement cost functions, removing fragments is significantly less expensive than removing intact objects. Second, the model assumes that the collision probability is the same for fragments and intact objects, making fragment removal more cost-effective in reducing overall collision risk. At this respect, McKnight et al. (2021) identify and rank the 50 most hazardous intact objects in low Earth orbit for targeted removal, using key risk factors such as mass, encounter rate, orbital lifetime, and proximity to operational satellites to promote space safety and sustainability.

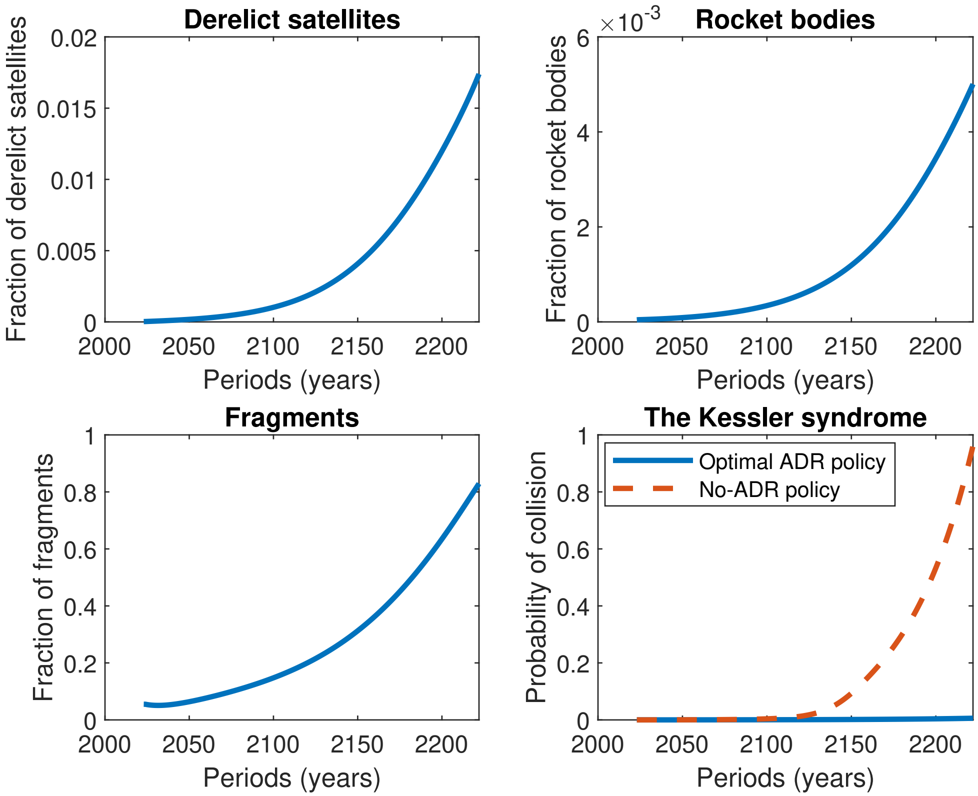

FIGURE 5. Optimal fraction of debris removed and probability of collision

This figure plots the optimal fraction measured as the percentage of orbital debris removed from orbit by ADR policies, and the probability of collision which is interpreted as an indicator of the likelihood of the Kessler syndrome.

We also report the estimated probability of collision under each scenario, which reflects the potential onset of a Kessler syndrome. In the scenario with optimal ADR implementation, the accumulation of orbital debris remains within acceptable levels. In contrast, without ADR interventions, the debris population grows unchecked over time. As a result, the probability of collision remains low and stable in the ADR scenario, due to effective control of the debris environment. Conversely, in the absence of ADR, the collision probability begins to rise significantly around the year 2150, increasing steadily and approaching one by the end of the simulation horizon.

Finally, Figure 6 presents abatement costs as a percentage of output. As space activity expands alongside economic growth, total abatement costs increase, driven by the rising costs of removing rocket bodies, fragments, and the overall debris population. On one hand, the cost of removing derelict satellites and rocket bodies is relatively high; however, because only a small fraction, particularly of rocket bodies, is removed, the associated abatement costs remain limited. As a result, the bulk of abatement expenditures

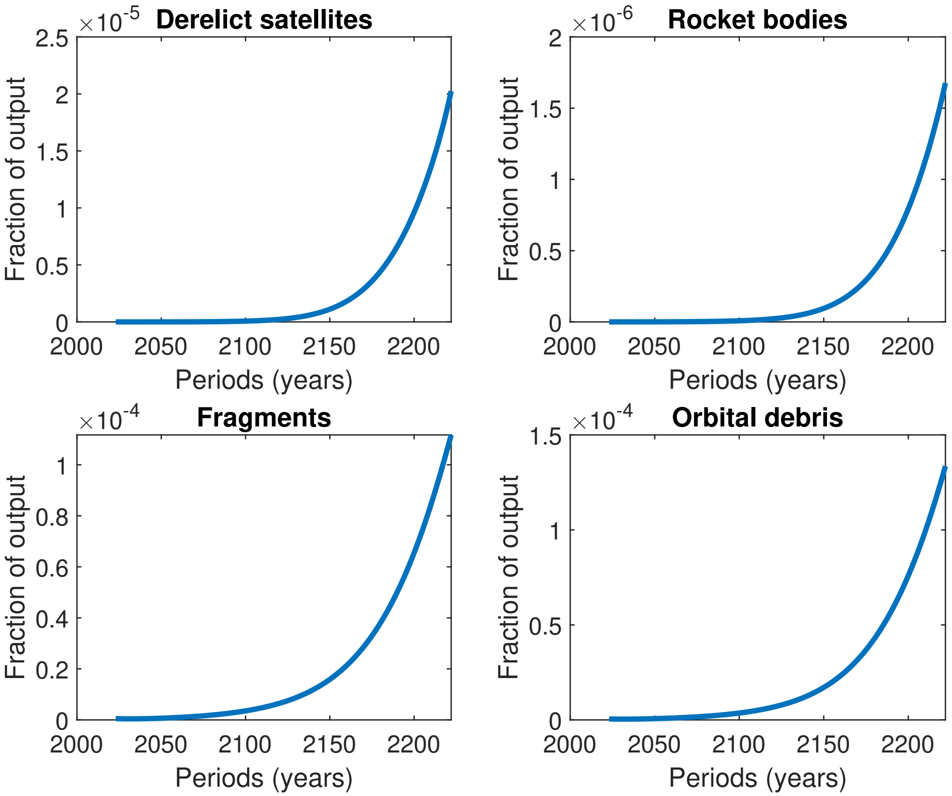

FIGURE 6. Abatement cost as a percentage of output

This figure plots the abatement cost in ADR policies as a percentage of output. Total abatement cost is the sum of abatement costs for derelict satellites, rocket bodies, and fragments.

are concentrated in fragment removal, which constitutes a more cost-effective strategy for mitigating collision risk.

Table 3 summarizes the main findings, presenting the values of key variables for the years 2100 and 2200. The orbital population and composition undergo dramatic shifts as a consequence of implementing ADR policies. As space activity increases, so does the need for debris mitigation, with the fraction of fragments removed at the year 2200 is above 63%. Abatement costs are projected to reach approximately 660 billion international dollars by 2200, in a context where global GDP is estimated at around 10,000 trillion dollars. Of this total, the cost of removing derelict satellites accounts for 97 billion dollars, corresponding to the elimination of just 1% of these objects. For the case of rocket bodies, the cost of removal at 2200 is only 8 billion dollars, as the optimal fraction of rocket bodies to be removed is already small.

With Optimal ADR in place, the number of launches by 2100 is expected to be 5,872, whereas in the absence of any ADR policy, this number would drop to 734. By 2200, the

TABLE 3. ADR versus non-ADR interventions

Variable	Optimal ADR-policy 2100	2200	No-ADR policy 2100	2200
Debris	4.53×10^6	3.08×10^7	3.05×10^7	4.26×10^9
Fragments	4.37×10^6	2.97×10^7	3.04×10^7	4.26×10^9
Derelict satellites	1.36×10^5	9.67×10^5	8.70×10^4	9.22×10^3
Rocket bodies	1.94×10^4	1.50×10^5	1.75×10^4	4.61×10^3
Operational satellites	8.59×10^4	6.62×10^5	5.19×10^4	7.92×10^4
Satellites destroyed by collision	49	2,546	198	4.23×10^4
Launches	5,872	2.15×10^5	734	4,052
Fragments removed (percentage points)	0.1477	0.6348	–	–
Derelict satellites removed (percentage points)	0.0010	0.0120	–	–
Rocket bodies removed (percentage points)	0.0003	0.0034	–	–
GDP (Trillion $)	1,284	10,069	1,282	10,005
Fragments abatement cost (Trillion $)	0.0046	0.6591	–	–
Derelict satellites abatement cost (Trillion $)	$9.03 \times 10^{-}5$	0.0968	–	–
Rocket bodies abatement cost (Trillion $)	$1.02 \times 10^{-}5$	0.0080	–	–

number of launches falls from 215,000 in 2100 to 4,052. Without an ADR policy, space becomes increasingly difficult to utilize due to the elevated risk of collisions. The volume of space debris across multiple categories debris, fragments, derelict satellites, and rocket bodies can be compared under scenarios with and without an optimal ADR policy. We find that the number of orbital debris, derelict satellites, rocket bodies, and fragments, is significantly lower when ADR policy is implemented. A particularly notable case is the number of derelict satellites in 2200, with an optimal ADR policy, the number reaches 967,000, while without such policy, it is only 9,220. This stark contrast reflects the unprofitability of space for commercial actors under high collision risks conditions, which leads to a sharp decline in space activity. When we focus on rocket bodies, the quantity decreases from 150,000 without ADR to just 4,610 with optimal ADR policy. Finally, the number of operational satellites increases from 79,200 to 660,000, further illustrating the decline in space operations when no effective debris mitigation strategy policy is in place.

For the year 2100 optimal ADR policies yield a 14.77% of fragments removed (a total of 646,040 debris fragments), whereas for the year of 2200 this fraction increases to a 63.48$ (1.88×10^7). By contrast percentages of removed derelict satellites and rocket bodies are much more smaller. For the year 2100 the fraction of derelict satellites removed is a 0.1% (139 derelict satellites), whereas the fraction of rocket bodies removed is a mere 0.03% (only 7 rocket bodies removed). By the year 2200 the fraction of derelict removed is 1.2% (six derelict satellites), and the fraction of rocket boodies is 0.34% (515 rocket bodies.)

6. CONCLUSIONS

Limiting the growth of orbital debris and avoiding the Kessler syndrome can be achieved through two main strategies: reducing debris emissions (ex-ante passive debris mitigation) or actively removing debris from orbit (ex-post active debris mitigation). Ex-ante passive mitigation policies have been extensively analyzed in Bongers and Torres (2025) within the framework of the DISE-2024 model. This paper focuses on optimal Active Debris Removal (ADR) policies aimed to cleaning up the space environment. We extend the DISE-2024 model to allow a central planner to determine the optimal ADR policy, tailored to each category of orbital debris. The model distinguishes among three types of debris: rocket bodies, derelict satellites, and fragments. The cost functions for ADR interventions targeting both intact objects and fragments are based on data from NASA (Colvin et al., 2023). Due to data limitations, the cost of removing rocket bodies and derelict satellites is assumed to be the same.

We find that the optimal fraction of rocket bodies and derelict satellites to be removed is relatively small compared to the optimal fraction of fragments targeted for removal. Although the model assumes that all types of orbital debris pose an equal collision risk, intact objects such as derelict satellites and rocket bodies can break up, generating additional fragments through an endogenous in-orbit debris creation process. However, the cost of removing fragments is significantly lower than that of removing intact objects. Based on cost estimates from NASA, our results show that optimal ADR policies can maintain a clean orbital environment, effectively reducing spacecraft losses due to collisions. Moreover, ADR policies enable and unconstrained expansion of the number of operational satellites.

Bongers and Torres (2025) find that passive debris mitigation policies, even when aligned with existing mitigation guidelines, are insufficient to limit the long-term growth of orbital debris and prevent the onset of the Kessler syndrome. Only the European Space Agency's (ESA) zero-debris approach has proven effective in maintaining a safe orbital environment. Even in a hypothetical scenario where all spacecraft could perfectly avoid collisions, the debris population would continue to grow exponentially. These findings highlight the urgent need to complement ex-ante debris emission mitigation policies with ex-post debris removal strategies to ensure long-term space sustainability. This paper demonstrates that, even in the absence of mandatory debris emission mitigation, Active Debris Removal (ADR) policies alone can curb the growth of orbital debris and keep the collision risk within tolerable limits. The challenge, however, lies in implementation. ADR policies require substantial international coordination and cooperation, fair cost-sharing mechanisms among spacefaring entities, and careful management of military sensitivities. The encouraging news is that there are precedents on Earth, such as the governance of the deep seas and Antarctica, where international collaboration and agreements have successfully addressed the tragedy of the commons (Hardin, 1998).

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