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DISE: A Dynamic Integrated Space-Economy Model for Orbital Debris Mitigation Policy Evaluation

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Abstract

This paper presents the Dynamic Integrated Space-Economy (DISE) model, designed to study the economic implications of alternative policies to mitigate orbital debris. The DISE model combines a standard neoclassical growth model with a physical space model for orbital debris dynamics. The economic model categorizes capital assets into two types: Earth's capital and Space's capital (i.e., satellites). The orbital debris model describes the dynamic of three types of objects: derelict satellites, rocket bodies, and fragments. DISE is intended to calculate the cost of space debris and its impact on the global economy. The model is simulated for a horizon of 200 years, starting from 2024, under different scenarios, including a clean space environment, laissez-faire, derelict satellites de-orbiting policy, all intact objects de-orbiting policy, debris-free launch systems, a combination of de-orbiting and debris-free launch vehicles, and collision avoidance. We find that the implementation of de-orbiting and debris-free launch systems mitigation policies is not enough to ensure space environmental sustainability, as in the long run the main source of debris generation would be collisions. Without any debris mitigation intervention, the cost of orbital debris would be more than 0.5% of world GDP in the long-run.

Keywords Outer space · Orbital debris · Satellites · Integrated assessment model · Mitigation policies

JEL Classification D62 · E22 · H23 · Q53 · Q58

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1 Introduction

Human activities in outer space began in 1957 with the launch of Sputnik I. Since then, the human presence in space has led to the creation of a unique form of pollution known as orbital debris or space junk.[1] The increase in orbital debris represents a significant challenge to human activities in outer space and could have further negative implications for humanity's well-being. This debris includes millions of objects, such as derelict satellites, rocket bodies, satellite fragments from explosions, tiny paint flakes, propellant drops, and even astronaut tools, all traveling at high speeds. Space pollution causes damage in the form of collisions and the destruction of operational satellites. When satellites are launched and operated, they create debris as a by-product that can collide with other satellites, leading to catastrophic results. Even collisions with small pieces of debris represent a severe risk because of the high speeds involved, impacting commercial, scientific, and defence activities in space. Various sources contribute to orbital debris, including parts of launch vehicles, upper stage rocket bodies, non-functional derelict satellites, and satellite breakups. In addition, space debris is self-propagating, as collisions among debris generate more fragments. This phenomenon is known as the Kessler syndrome (Kessler and Cour-Palais 1978; Kessler 1981, 2010), which describes a scenario of collisions among orbital debris in a cascade.

The issue of orbital debris has recently received attention from economists, who have been developing different analytical frameworks, for instance, combining an economic model with a physical model. These initial attempts to merge economic and space variables models include Adilov, Alexander and Cunnigham (), Macauley (2015) and Rouillon (2020). Adilov et al. (2015) compare the optimal number of launches in a decentralized versus a centralized market and found that the number of satellites and launches is higher than the social optimum as firms do not consider the negative externality of debris generated by their activities in space. Adilov et al. (2018) used a net present value approach to determine that the threshold level of debris for economic viability is lower than the'Kessler syndrome' level identified by Kessler and Cour-Palais (1978). Macauley (2015) presented different technological strategies to mitigate debris generation and/or collision risk, including manoeuvring capability, grave-yarding capability and shielding. Several papers focus on the use of alternative policy instruments (i.e., taxes) for internalizing the social cost of orbital debris, such as Grzelka and Wagner (2019), Adilov et al. (2020), Béal et al. (2020), Rao et al. (2020), Rouillon (2020) and Bernhard et al. (2023).

More recently, the literature has developed some aggregated integrated assessment models (IAMs) for the space. Adilov et al. (2020) simulate a simple model for the quantity of orbital debris under alternative scenarios (such as compliance with space debris mitigation guidelines, launch tax, and active debris removal policies). Rao and Letizia (2022) combine an econometric model for space activity with a debris environment model based on a Particle-in-a-Box (PIB) framework. Another example of IAM for orbital debris is the OPUS (Orbital Debris Propagators Unified with Economic Systems) model suggested by Rao et al. (2023). OPUS incorporates an astrodynamic propagator to assess the state of objects in orbit combined with a simple economic model to determine launch activity. The model is used to evaluate policy proposals for managing orbital congestion. Rao and Rondina (2025) focus

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[1] Orbital debris can be natural (meteoroids) or human-made (junk). This paper focuses on the latter. NASA defines orbital debris as any human-made object in orbit that no longer serves a useful purpose, including spacecraft fragments and retired satellites.

on study the conditions under which the Kessler syndrome, defined as a situation in which the level of objects implies that the orbit will eventually become unusable in finite time, can be optimal in a centralized economy. Lee et al. (2024) estimates the loss of value of satellites due to orbital debris for South Korea using a contingent valuation approach.

In recent studies, neoclassical growth models have analyzed human activity in outer space. Nozawa et al. (2023) developed a macroeconomic growth model that includes a satellite sector with collision risk. They found that the proliferation of orbital debris could lead to a long-term decline in global GDP of 1.95% if no remedial actions are taken. Corrado et al. (2023) proposed a model with endogenous growth and the space sector, showing that space investment and technological spillovers play a significant role in economic growth. They find that the growth spillover from technological change in the space industry is much lower in recent years compared to the period between 1960 and 1980. Fleming et al. (2023) applied a growth model to study the implications of asteroid mining. Their framework assumes that the economy produces only one metal, whether extracted from Earth or outer space, without limitation. They found that transitioning from mining on Earth to space allows for continued growth in metal use and limits environmental damage on Earth caused by mineral extraction.

This paper is a further step in integrating the space environment with economics. The purpose of this paper is twofold. First, this paper evaluates the long-run implications and effectiveness of implementing different debris mitigation guidelines developed by international organizations, such as the Inter-Agency Space Debris Coordination Committee (IADC) of the United Nations, and the different national space agencies, for assessing space sustainability in the long-run. Second, the paper estimates the cost, measured as forgone world output, of space pollution with orbital debris. This paper also contributes to the literature by introducing an integrated assessment model (IAM) for the global economy and the outer space environment, specially designed to evaluate some non-active mitigation policies to handle the problem caused by orbital debris. IAMs have proven to be useful theoretical frameworks for assessing the links between the economy and the environment. Similar to environmental and climate change IAMs, the model consists of two parts: an economic component that aims to provide insight into the decisions that drive outer space business activities and a physical space component that offers information about the impact of those activities on the space environment. Building on the tradition of IAMs like Nordhaus's (1992, Nordhaus 1993) DICE model, which is used in environmental economics and climate change research. This study combines orbital debris generation dynamics with the selection of optimal policies to create an economy-space model called DISE (Dynamic Integrated Space-Economy) model.

The economic core of DISE is a two-capital inputs dynamic general equilibrium growth model that includes the dynamics of outer space environment. In this model, aggregate output is a function of physical capital on Earth (equipment and structures) as well as in outer space (satellites). However, launching and operating satellites creates pollution in the form of fragments (orbital debris) made of different materials, which travel at high speeds and can collide with operational satellites. The model incorporates the negative externality that arises from the accumulation of orbital debris, which depends on current and past debris levels. Debris also undergoes natural depreciation due to atmospheric drag. In this theoretical framework, orbital debris not only reduces current output by reducing the stock of space capital in case of collision, but also affects future output by disrupting the accumulation of space capital.

The IAM presented in this paper is a modification of the dynamic stochastic general equilibrium (DSGE) model for the global economy and the space by Bongers et al. (2024) for the study of optimal active debris removal (ADR) policies over the business cycle under a centralized economy where the central planner selects the optimal level of abatement and under a Ramsey international authority, which charges a satellite tax to fund the ADR policy. In this paper, we develop a deterministic version of that model, which includes two exogenous technological sources of growth. We have also extended the physical part of the model to incorporate a more detailed orbital debris evolutionary model. The growth model is partially optimal because firms aim to maximize profits, while households choose the optimal investment allocation between Earth's and Space's capital based on a given saving rate. The assumption of an exogenous saving rate has been widely used in the literature on climate change IAMs (see, for instance, Golosov et al. 2014; Dietz and Stern 2015; Fankhauser and Tol 2005).

With the calibrated model at hand, various simulations were conducted to explore different policy scenarios. The simulations were carried out over a 200-year period (from 2024 to 2224). The baseline scenario assumed a hands-off (laissez-faire) regime with no intervention. Other scenarios examined include the implementation of a mandatory de-orbiting policy for satellites reaching the end of their operational life, a scenario where the mandatory de-orbiting policy is extended to upper stages rocket bodies, a scenario in which launch systems were debris-free and fully reusable, and a scenario in which no collisions occurred due to advanced tracking and avoidance maneuverability. In addition, the study also looked at a scenario without space pollution to assess the cost of orbital debris. We find that, without any debris mitigation intervention, the cost of orbital debris would be larger than 0.5% of world GDP in the long-run. By contrast, the different debris mitigation policies produce output gains from 0.05% to 0.6% of world GDP compared to the laissez-faire scenario.

Based on our model simulations, we identified four key findings. First, as output increases, so does the number of satellite launches and the total number of satellites in orbit, leading to a gradual rise in orbital debris. This accumulation results in more collisions with operational satellites, ultimately reducing the optimal number of satellites in orbit, except in scenarios where collisions are absent. Second, the primary sources of debris production evolve over time. Initially, launches (mission related objects) and the breakup of satellites and rocket bodies are the dominant contributors. However, as the number of satellites in orbit increases, collisions between debris and operational satellites become the leading source of new debris. Third, our baseline model calibration reveals that the number of satellites begins to decline before the probability of collision reaches one, even if economic growth remains positive and Earth's capital continues to accumulate. We interpret this tipping point as an indication of an "economic" Kessler syndrome. Finally, debris mitigation policies, such as de-orbiting measures, preventing rocket body breakups and derelict satellites, and developing debris-free launch systems, can effectively reduce orbital debris in the short and medium term. However, in the long run, their positive impact is limited due to the existing level of orbital pollution, and to the endogenous in-orbit process of debris generation.

The organization for the rest of the paper is as follows. Section 2 presents a global economy-space model developed to show the relationship between the final output and the number of satellites in outer space potentially impacted by orbital debris. Section 3 describes the model solution for a decentralized economy for optimal investment allocation between two types of capital assets. Section 4 focuses on parameterization and calibration of the model. Section 5 describes the policy experiments to be conducted with the calibrated model. Section 6 presents the results from model simulations for alternative scenarios. Finally, Section 7 provides some conclusions.

2 The Dynamic Integrated Space Economy (DISE) Model

This section presents an overview of the structure of the DISE model. DISE is an integrated assessment model (IAM) that incorporates human activity in space into a global economic model. Like other IAMs used in environmental and climate-change economics, the theoretical framework comprises two submodels: an economic model and a physical model for the stock of orbital pollution. The economic model is based on the neoclassical growth model for the world economy. Satellites are considered an additional type of capital alongside Earth's capital in the aggregate production function. Therefore, this model encompasses human economic activities on Earth and in outer space.

The economic aspect of DISE is built on a partial optimal dynamic general equilibrium growth model with an exogenous saving rate. In the model, the representative household represents humankind. Hence, this can be interpreted as the model implicitly assuming that humankind is the owner of outer space, which is a global common. The output allocation is divided into consumption, investment in physical capital on Earth, and investment in satellites. In this framework, firms aim to maximize profits, while households choose the optimal investment allocation between Earth's and Space's capital, given a fixed saving rate. The model takes into account a negative externality resulting from orbital debris pollution in outer space. Unlike standard environmental economic models, pollution does not directly reduce output by decreasing aggregate productivity. The cost of pollution in Earth's orbit arises from the fact that orbital debris increases the risk of collision and, consequently, the potential destruction of operational satellites. This leads to a decrease in the stock of in-orbit equipment and a decline in production if destroyed equipment is not replaced. It's worth mentioning that the damage function in the DISE model is significantly more straightforward than in climate change IAMs, but emissions (debris production) show greater complexity. Finally, the model does not include any abatement cost function. This means that we assume that the different compulsory debris mitigation policies can be implemented at no cost. This assumption does not affect the results as the economic submodel is a partial-optimal growth model, where saving is exogenous.[2]

The physical model is a simplified representation of the evolution of orbital debris. Non-operational objects in orbit are divided into three categories: derelict satellites, rocket bodies, and fragments. An accumulation equation describes the dynamics of each type of orbital debris. The quantity of derelict satellites is determined by de-orbiting operations performed by satellite operators at the end of a satellite's operational life. The quantity of rocket bodies is influenced by the number of launches and the type of launch vehicles used. Lastly, the

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[2] The model is a partial-optimal growth model where the aggregate saving rate is exogenous. The introduction of abatement costs for the implementation of the different debris mitigation policies in the feasibility condition for the economy would simply imply an equivalent reduction in consumption, with no consequence on the rest of the variables, except for the household's utility.

quantity of fragments is affected by the breakups of derelict satellites and rocket bodies, as well as other sources such as collisions and mission-related objects.

Finally, the model incorporates a mapping between physical variables of the space sector (number of launches, number of satellites, number of orbital debris, etc.) and the corresponding variables of the economic model. Physical variables are represented by capital letters, while economic output-measured variables are written in lowercase letters. This worldwide model uses aggregate variables for economic variables (world output, total Earth's capital, etc.) and physical variables (average size and mass of satellites and size of orbital debris, average altitude, etc.)

2.1 The Economy Model

There is a representative household with utility $U(c_t)$, defined over consumption c_t. The stand-in household represents humankind which is the owner of outer space. This household satisfies the following budget constraint, aligning with the final-good sector's feasibility constraint:

$$c_t + i_t + h_t = y_t \tag{1}$$

where i_t is investment in physical capital other than satellites, and h_t is investment in satellites, including all costs to insert satellites into orbit. The price of consumption and investments are defined in output units and normalized to one.

Output is assumed to be a function of aggregate productivity, the stock of physical capital on Earth, k_t, and the stock of satellites, s_t,

$$y_t = a_t f(k_t, s_t) \tag{2}$$

where a_t is the total factor productivity (TFP). Labor has been normalized to one and no population growth is considered.

The standard inventory equation describes the capital accumulation process, excluding satellites:

$$k_{t+1} = (1 - \delta_k)k_t + i_t \tag{3}$$

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,

$$s_{t+1} = (1 - \delta_s)s_t + q_t h_t - x_t \tag{4}$$

where $0 < \delta_s < 1$ is the depreciation rate for satellites, and x_t is the loss of satellite assets by collisions (damage from pollution) to be defined later. Damage results in the destruction of satellites, the reduction of stock used in production, and the reduction of the final output if the asset is not replaced.[3] The law of motion for the stock of satellites considers an invest-

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[3] Orbital debris is not the only existing externality in Earth's orbit. Other externalities are congestion at particular altitudes, electromagnetic pollution, and radio-spectrum interference of nearby satellites.

ment-specific technological change (ISTC) component, denoted by q_t(see Greenwood et al. 1997). ISTC indicates that the cost of space assets (i.e., launch prices) tends to decrease over time. This trend is not only a result of the learning-by-doing process but also reflects the growing competitiveness within the space industry over time.

Output growth depends on two sources of technological change: Neutral technological change (TFP growth) and ISTC in satellite assets. Similarly to climate change IAMs, neutral technological progress is characterized as,

$$a_{t+1} = exp(g_{a,t})a_t \tag{5}$$

where $g_{a,t}$ is the TFP growth rate, and where,

$$g_{a,t} = g_{a,0}exp(-\delta_a t) \tag{6}$$

where δ_a is the decay rate in the TFP growth rate. We assume a similar specification for the satellite investment-specific technological progress, where,

$$q_{t+1} = exp(g_{q,t})q_t \tag{7}$$

where $g_{q,t}$ is the satellite's ISTC growth rate, and where,

$$g_{q,t} = g_{q,0}exp(-\delta_q t) \tag{8}$$

where δ_q is the decay rate in the satellite's ISTC growth rate.

2.2 Mapping Between Economic and Physical Variables

A mapping between economic and physical variables is required to calibrate the model's parameters accurately and to generate physical values for the number of launches and satellites for comparison with the data. The first step in creating this mapping involves connecting the stock of satellites as a capital asset to output units, s_t, with the number of satellites, S_t, given by,

$$S_t = \mu s_t \tag{9}$$

where the parameter μ is the conversion parameter that transforms "economic" values into "physical" values. Similarly, the number of satellites destroyed by collisions, X_t, is

$$X_t = \mu x_t \tag{10}$$

A second mapping between investment in satellites and the number of new satellites deployed into orbit is also considered, N_t,

$$N_t = \mu q_t h_t \tag{11}$$

where the satellite's ISTC determines the number of new satellites per unit of investment. A higher value of q_t corresponds to a greater number of new satellites per unit of investment, which can be interpreted as a decrease in the relative price for satellite investment. In practical terms, a positive trend in q_t suggests reducing satellite launching and manufacturing costs.

By substituting the above mappings into the restriction Eq. (4), we can derive the accumulation process for the number of satellites. Therefore, the stock of satellites, as measured by the number of representative satellites, can be expressed as,

$$S_{t+1} = (1 - \delta_s)S_t + N_t - X_t \tag{12}$$

where $0 < \delta_s < 1$ is the depreciation rate of satellites. Therefore, each period, the amount $\delta_s S_t$ of satellites becomes non-operational and, hence, considered orbital debris of derelict satellite type, in case they are not removed from orbit.

2.3 Launches

The number of launches is crucial in the model. It is important to consider the number of launches as an additional auxiliary variable because the primary source of debris emission is the launch process. Standard launch systems use rockets with several (up to four) stages. Some equipment deployed at the different launching stages, such as fuel tanks and engines, remains in orbit once the payload reaches its target al.titude. Moreover, additional pieces of debris, such as fairings, are generated during the insertion phase. However, recent technological advances in launch systems have introduced reusable vehicles that do not produce debris. The number of launches is distinct from the number of satellites placed in orbit, as technological advances in the industry have led to the development of heavier launch vehicles with higher payload capacities. Simultaneously, the reduction in the size and weight of satellites allows multiple satellites to be deployed with a single launch. Consequently, we need to consider the number of launches separately from the number of newly deployed satellites. In fact, during the past decade, there has been a rapid increase in the number of satellites launched per mission, driven by the availability of more powerful launch vehicles and the decrease in the size and weight of satellites. As a result, the number of satellites deployed in orbit, N_t, is assumed to be a proportion η of the number of launches, L_t.

$$N_t = \eta L_t \tag{13}$$

and therefore, the parameter η can be interpreted as the number of satellites per launch. From here, we can obtain the relationship between investment in satellites, the value of launches, and the number of launches given by,

$$h_t = \frac{\eta}{q_t} l_t = \frac{\eta}{\mu q_t} L_t \tag{14}$$

2.4 The Space Model

The physical space model consists of three main functions: the damage function, the emission (debris generation) function, and the motion of the stock of orbital debris. Needless to say, the space environment is significantly different from Earth. Space pollution can be natural or artificial and threatens space equipment due to high-speed collisions. This paper focuses explicitly on man-made space debris, as natural space pollution is rare and minimally represents a risk to humans, except when a relatively large object is on a collision course with Earth. Any non-functional object orbiting Earth is considered space junk. The Earth's atmosphere protects against smaller objects colliding with our planet, confining any resulting damage to space. Although it is unlikely, it can happen that some uncontrolled large-mass debris in low orbit may enter the Earth's atmosphere and potentially cause damage to life or property.

2.4.1 Damages

Human activities in outer space create pollution in the form of orbital debris traveling at high speeds. On average, this debris travels at 36,000 km/h or ten kilometers per second in the Low Earth Orbit (LEO). Collisions of this debris with operational satellites and other spacecraft can lead to the loss of space equipment.

The literature contains various methods for calculating the likelihood of collisions in space. We consider a simple damage function that relies on the number of satellites and the quantity of orbital debris greater than 1 cm. As proposed by Farinella and Cordelli (1991), the number of satellites destroyed in each time period as a result of collisions with debris is assumed to be a function of the amount of debris and operational satellites.

$$X_t = \theta D_t S_t \tag{15}$$

where $\theta > 0$ is a parameter that represents the probability of collision and D_t is the number of orbital debris. According to the above expression, and using the mapping parameter, the value of satellite assets destroyed by a collision, x_t, is defined as,

$$x_t = \theta D_t s_t \tag{16}$$

When $\theta D_t = 1$, it results in the destruction of any space assets, making the space unusable. This threshold is reached when the pollution stock is $D_t = 1/\theta$. This situation is known as the "Kessler syndrome," as defined by Adilov et al. (2018).

2.4.2 The Stock of Pollution

The stock of orbital debris is measured by the number of non-operative human-created objects in Earth's orbit. Before the first satellite launch, Sputnik I, in 1957, there was no orbital debris, as humans had not yet ventured into space. The stock of debris, denoted as D_t, can be defined as:

$$D_t = W_t + Z_t + F_t \tag{17}$$

where we distinguish three types of debris: W_t represents the stock of dead satellites abandoned in orbit, Z_t is the number of upper stages rocket bodies left in orbit from launches, and F_t denotes fragments that cannot breakup except in case of collision. Meanwhile, both derelict satellites and rocket bodies can disintegrate, creating even more fragments or they can collide with each other or with fragments.

2.4.3 Debris Generation

Debris comes from different sources, such as discarded rocket stages, defunct satellites left in orbit, accidental explosions, mission-related objects, collisions, and intentional actions like the destruction of a satellite using anti-satellite missiles in military drills. According to the European Space Agency (2024), until the end of 2023, there have been over 645 breakups, explosions, collisions, or anomalous events leading to fragmentation.

The model addresses five main sources of debris resulting from collisions and launches. The first source of space debris is mission-related objects (MRO), connected to the number of launches. We assume that the process generating this type of debris follows the expression ωL_t, where ω represents the number of debris pieces generated in each launch during lift-off. This debris is classified as “fragments” and includes protective fairings, covers, adapters, bolts, and cables.

In addition to these fragments, launches generate another type of debris related to the launch vehicle technology. The final stages of launch vehicles often remain in orbit after payload deployment. These rocket bodies are large pieces of debris with the risk of further fragmentation. We assume that the number of rocket bodies produced per launch follows the expression φL_t, where $0 < \varphi < 1$ represents the fraction of launches that generate this type of debris. This fraction is strictly less than one to account for the existence of reusable launch vehicles or upper stage rocket post-mission disposal. Over time, these rocket bodies accumulate in orbit, contributing to the stock of debris.

The third source of space debris is derelict satellites, denoted as W_t. Derelict satellites are non-operational satellites that are no longer in use, usually because they have run out of fuel. They are left floating in space instead of being brought back to Earth. In each period, the number of satellites that become non-operational is $\delta_s S_t$. A fraction χ of non-operational satellites is left floating in space. The number of abandoned end-of-life satellites in orbit may vary depending on the guidelines in place for satellite disposal at the end of their missions. If all non-functioning satellites are required to return to Earth (de-orbited), the number of satellites in orbit, denoted as W_t, would decrease over time due to natural decay and occasional explosions.

The fourth source of space debris is fragmentation events caused by explosions and the breakup of derelict satellites, rocket bodies, and engines. These explosions in orbit are primarily caused by the remaining fuel in tanks or lines after a rocket stage or satellite enters Earth’s orbit. The extreme space environment can gradually weaken the structural integrity of external and internal components, causing leakages or mixing of fuel components, which could trigger self-ignition. In addition, batteries can also explode, leading to further fragmentation. As a result, the explosion can destroy the original object and disperse its mass into fragments of different sizes and velocities. Finally, the fifth source of debris is collision and fragmentation between objects. The model considers three types of collisions: collision of operational satellites with debris, collisions of derelict satellites with each other and with other debris, and collision of rocket bodies with each other and with other debris.

The laws of motions for each type of orbital debris are formalized as follows. The movement of derelict satellites over time is described as:

$$W_{t+1} = (1 - \delta_d - \delta_w)W_t - \theta D_t W_t + \chi \delta_s S_t \tag{18}$$

where the natural decay rate of debris, denoted as δ_d, represents how quickly debris disintegrates over time. The fraction of derelict satellites that explode each period is denoted as δ_w. The natural depreciation rate of debris varies significantly based on altitude. Debris has a high natural depreciation rate at low altitudes, resulting in a short lifespan. However, as altitude increases, the natural depreciation rate decreases exponentially. At high altitudes, the natural depreciation rate of debris approaches zero. The number of debris produced by the breakup of derelict satellites is given by $\sigma \delta_w W_t$. The term $\theta D_t W_t$ accounts for the number of collisions of derelict satellites with each other, with rocket bodies and with fragments.

Similarly, the dynamic equation for the stock of rocket bodies (upper stages of launch systems) is defined as,

$$Z_{t+1} = (1 - \delta_d - \delta_z)Z_t - \theta D_t Z_t + \varphi L_t \tag{19}$$

where δ_b represents the fraction of body rockets that break up each period, and the term $\theta D_t Z_t$ represents the number of rocket bodies which collide with each other, with derelict satellites and with fragments. The number of debris produced by the breakup of rocket bodies is given by $\rho \delta_z Z_t$.

Finally, the law of motion of fragments is given by,

$$F_{t+1} = (1 - \delta_d)F_t + \omega L_t + \sigma \delta_w W_t + \rho \delta_z Z_t + \gamma X_t + \varepsilon \theta D_t W_t + \nu \theta D_t Z_t \tag{20}$$

where γ is the amount of debris generated by a collision and destruction of operational satellites, and ω is the amount of debris produced per launch. In addition, explosions and breakups of derelict satellites generate fragments in the quantity given by σ, and explosions and breakups of rocket bodies generate fragments in the quantity given by ρ. The parameters ε and ν represent the number of fragments produced by the collision of derelict satellites and rocket bodies, respectively, with each other and with fragments.

3 Laissez-Faire Competitive Decentralized Equilibrium

First, we consider the case of a competitive decentralized economy without any mitigation policy (no intervention). This is the baseline scenario (laissez-faire). In this setup, households and firms make decisions without considering the social cost of the negative externality resulting from orbital debris, leading to damages that are not internalized. They adjust their decisions to the space environment. This realistic description reflects the current situation in space, where no central authority exists and spacefaring entities only take passive measures to protect themselves from debris collisions. Consequently, satellite investment decisions incorporate the cost of collisions as an exogenous given cost.

The household's maximization problem is defined as,

$$\max_{\{c_t,k_t,s_t\}_{t=0}^{\infty}} E_0 \sum_{t=0}^{\infty} \beta^t U(c_t) \tag{21}$$

where $0 < \beta < 1$ is the discount factor and E_0 is the expectation operator at time $t = 0$, subject to the budget constraint given by,

$$c_t + i_t + h_t = r_t^k k_t + r_t^s s_t + \pi_t \tag{22}$$

where r_t^k and r_t^s are the rental prices of capital and satellites, respectively, and π_t is the firm's profit, all of them exogenous to the household. The household's maximization problem considers the accumulation process for both capital and satellites. It is as follows:

$$\begin{aligned} \mathcal{L} = E_0 \sum_{t=0}^{\infty} \beta^t U(c_t) \\ - \sum_{t=0}^{\infty} \lambda_{1,t} [c_t + k_{t+1} - (1-\delta_k)k_t + \frac{1}{q_t}[s_{t+1} - (1-\delta_s)s_t + \theta D_t s_t] \\ - r_t^k k_t - r_t^s s_t - \pi_t] \end{aligned} \tag{23}$$

From the first order conditions for the household's maximization problem, equilibrium conditions, for $t = 0, 1, \ldots, \infty$, are given by,

$$U'(c_t) = \beta E_t U'(c_{t+1})[1 - \delta_k + r_{t+1}^k] \tag{24}$$

$$U'(c_t) = q_t \beta E_t U'(c_{t+1}) \left[\frac{1 - \delta_s - \theta D_{t+1}}{q_{t+1}} + r_{t+1}^s \right] \tag{25}$$

Expression (24) represents the standard Euler equation for investment in Earth's capital. Meanwhile, expression (25) is also an Euler equation for the satellite investment decision, which includes the cost of destruction by collision of the asset. The term θD_{t+1} takes into account the sudden total depreciation of the stock of satellites due to collisions. As the quantity of orbital debris increases, the required rental prices of satellites to capital also increase.

The representative firm maximizes profits by choosing the appropriate levels of capital and satellites. Profits are defined as,

$$\pi_t = y_t - r_t^k k_t - r_t^s s_t \tag{26}$$

From the profit maximization problem, we obtain the standard conditions that equal the rental price to the marginal productivity:

$$r_t^k = a_t f_k'(k_t, s_t) \tag{27}$$

$$r_t^s = a_t f_s'(k_t, s_t) \tag{28}$$

Assuming perfect foresight and combining expressions (24), (25), (27), and (28), the competitive equilibrium implies that,

$$[1 - \delta_k + a_{t+1} f_k'(k_{t+1}, s_{t+1})] = q_t \left[\frac{1 - \delta_s - \theta D_{t+1}}{q_{t+1}} + a_{t+1} f_s'(k_{t+1}, s_{t+1}) \right] \tag{29}$$

The above expression indicates the optimal allocation of total investment between Earth's capital and satellites.

When solving the model numerically, we assume a fixed saving rate, following the approach of Golosov et al. (2014) and Dietz and Stern (2015). Dietz and Stern (2015) conducted simulations of different versions of the DICE model with a calibrated long-run average optimal saving rate of 25% in the absence of climate damage and emissions abatement costs. They argue that endogenizing the saving rate has little impact on the standard DICE model. Fankhauser and Tol (2005) also demonstrated that the saving rate has minimal effect on the model's simulation. Similarly, Hwang (2017) found that while setting the savings rate does not significantly impact the results, it substantially reduces computational workload. Furthermore, the savings rate remains relatively stable and gradually approaches a constant value as the economy converges toward equilibrium. Given the relatively constant nature of the savings rate, we consider it a valid approximation. In this context, firms aim to maximize profits. However, with the fixed saving rate, we solve a maximization problem for households to allocate between Earth's capital and satellites optimally. Therefore, the total investment is the sum of investment in Earth's capital and space's capital, is given by:

$$i_t + h_t = \phi y_t \tag{30}$$

where $0 < \phi < 1$ is the saving rate.

4 Model Parameterization, Data, and Calibration

Our model includes two types of parameters: economic and physical space parameters. It considers the global economy and the characteristics of outer space as a global common resource. A significant challenge in aggregating space-related variables is their dependence on altitude. Therefore, average values are used to calibrate the parameters of the model. Two parameters are particularly critical to understanding the dynamics of space debris: the debris decay rate and the collision risk.

Orbital decay occurs due to various mechanisms that diminish an object's orbital energy, such as atmospheric drag, gravitational anomalies, and electromagnetic interference. The decay rate of space objects is influenced by gravitational forces and atmospheric drag, which fluctuate with altitude. The decay rate of debris is inversely related to altitude; as altitude increases, the decay rate decreases, resulting in longer orbital lifetimes for debris. For instance, debris in orbits above 600 km typically re-enters Earth's atmosphere within several years, while debris below 200 km may decay within hours. Conversely, debris at altitudes above 1,000 km may remain in orbit for thousands of years. The collision risk parameter is similarly altitude-dependent, varying with the density of debris and operational satellites at different orbital regions. Certain orbits are heavily populated with satellites and debris, increasing collision probabilities, while others are relatively clear.

We use various databases on debris dynamics and the space environment to calibrate the parameters for our model. Paying attention to NASAs cataloged objects (NASA 2024), the calibration focuses on fragments larger than 10 cm. There are over 8,410 satellites in Earth's orbit, with around 5,600 still operational. The United States Space Surveillance Network (SSN) is tracking approximately 31,150 pieces of debris. There have been roughly 630 documented incidents involving fragmentation, including break-ups, explosions, collisions, or other unusual events. One of the most significant incidents was the collision on February 10, 2009, between an active U.S. communications satellite (Iridium 33) and a defunct Russian military communications satellite (Kosmos 2251). This collision created around 2,200 pieces of debris, each at least 5 cm in size (NASA 2007). Another critical event was an anti-satellite military test conducted on January 1, 2011, which destroyed the Chinese satellite Fengyun-1C with a kinetic weapon, resulting in approximately 3,037 new pieces of tracked debris.

Most of the orbital debris fragments are in two main areas: Low Earth Orbit (LEO, 200–2,000 km) and Geostationary Orbit (GEO, 35,786 km). The classification of orbital debris depends on its size and our ability to track these objects. According to various models, such as the LEO-to-GEO Environment Debris Model (LEGEND), there are approximately 36,500 pieces of debris larger than 10 cm, around 1,000,000 objects between 1 cm and 10 cm, and more than 130,000,000 fragments ranging from 1 mm to 1 cm. Debris smaller than 1 cm generally represents a low risk of catastrophic satellite damage, but it can still significantly impair critical systems and reduce operational lifespan. On the other hand, debris larger than 1 cm can be very dangerous due to the high speed of collisions. Therefore, our model calibration pays attention to the estimated quantity of debris larger than 1 cm using a proportional rule based on tracked debris from the LEGEND model.[4]

4.1 Model Parameterization

The production function is assumed to follow the Cobb-Douglas type, where labour is normalized to one,

$$y_t = a_t k_t^{\alpha_1} s_t^{\alpha_2} \tag{31}$$

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

No specific function is needed for the utility function, as the saving rate is exogenous, and the form of the household's utility does not affect the optimal allocation of total investment between Earth's and Space's capital.

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[4] In general, the literature considers that fragments smaller than 1 cm can damage a satellite but are unlikely to have fatal consequences (Krisko 2007; Mains et al. 2024). Fragments ranging from 1 cm to 10 cm can cause critical damage to vital parts of the impacted satellite. Fragments larger than 10 cm are considered lethal.

4.2 Calibration of Economic Parameters

The model is designed to be global and includes all human economic activities on Earth and in Space. The calibration considers all these human economic activities. The United States is the leading spacefaring country, and US companies like SpaceX and Blue Origin dominate the private spacefaring industry. Many countries are also entering the space industry and developing spacecraft launch capabilities. Therefore, the model's calibration is for an artificial global economy and a global common outer space.

The model calibrates a few economic parameters: the technological parameters for the production function, the saving rate, and the depreciation rates for physical capital and satellites. We use standard values from the existing literature for these parameters and activity data to calibrate the output-satellites elasticity parameter. Additionally, the model incorporates two technological growth processes: total factor productivity and investment-specific technological changes in satellites. Table 1 shows a summary of the calibrated values.

It is assumed that the sum of technological parameters for capital is $\alpha_1 + \alpha_2 = 0.35$, which implies a labour share of 0.65. Corrado et al. (2023) calibrate the space sector share on the whole economy to be equal to 0.0056. According to the Bureau of Economic Analysis Bernhard et al. (2023), the Space industry contributed $129.9 billion to the US economy

Table 1 Baseline calibration of the parameters of DISE

	Parameter	Definition	Value	Source
Economy	α_1	Earth's capital elasticity	0.3479	BEA
	α_2	Space's satellite elasticity	0.0021	BEA
	δ_k	Capital depreciation rate	0.07	Standard
	δ_s	Satellite depreciation rate	0.15	ESA/NASA
	ϕ	Steady-state saving rate	0.243	Internal calibration
	g_a	TFP growth rate	0.01	Assumption
	g_q	Satellite ISTC growth rate	0.03	Assumption
	δ_a	TFP growth decay rate	0.005	Assumption
	δ_q	ISCT growth decay rate	0.005	Assumption
	μ	Conversion parameter	383,090	Internal calibration
Space	η	Satellites per launch	10	ESA/NASA
	θ	Collision risk	1.25×10^{-19}	ESA/NASA
	χ	Fraction of abandoned satellites	0.35	ESA/NASA
	δ_d	Debris decay rate	0.01	NASA
	δ_w	Fraction of dead satellites breakups	0.002	ESA/NASA
	δ_z	Fraction of body rocket breakups	0.001	ESA/NASA
	φ	Body rockets abandoned per launch	0.80	ESA/NASA
	ω	Number of fragments per launch	4.00	ESA/NASA
	σ	Number of fragments per derelict satellite breakup	44.6	NASA
	ρ	Number of fragments per rocket body breakup	100.2	NASA
	γ	Number of fragments per operational satellite collision	100	ESA/NASA
	ε	Number of fragments per derelict satellite collision	100	ESA/NASA
	ν	Number of fragments per rocket body collision	100	NASA

in 2021 (0.6% of GDP). It provided 360,000 full-time and part-time jobs in the private space industry. The Space Foundation (2023) estimates that the global space economy will impact \$546 billion in 2022. The Satellite Industry Association Satellite Industry Association (2023) estimates that the global space economy represents \$384 billion for the year 2022. Nozawa et al. (2023) calibrated a Cobb-Douglas production function with labour, capital, and satellites, using a value of 0.002 for the elasticity of output to the stock of satellites. To calibrate the output elasticity parameter for satellite equipment, we used data from Bongers and Torres (2023) as 0.006×0.35, resulting in $\alpha_2 = 0.0021$. Therefore, $\alpha_1 = 0.3479$.

The Earth's capital depreciation rate is fixed to $\delta_k = 0.07$. For the Space's capital, we consider that a satellite's lifespan depends on its technical characteristics and the extreme environmental conditions present in outer Space. According to Gallois (1987), factors such as the type of satellite, as well as electrical, mechanical, physical, and gravitational aspects, play a crucial role in determining how long a satellite will remain operational. One significant limitation is the satellite's fuel capacity. The lifespan of satellites varies depending on their type and orbit. CubeSats, miniaturized satellites, have a lifespan of around six months, while GEO satellites can last up to 15 years. LEO satellites typically last between 3 and 8 years. To simplify calculations for any orbit, we consider an average annual depreciation rate of 0.15 for satellites. The saving rate is calibrated to the steady state saving rate, $\phi = 0.243$(see Barro and Sala-I-Martin 2001).,

The parameters for the exogenous technological sources of growth have been selected following the literature to generate an initial growth rate of approximately 2%. The initial TFP growth rate is set to $g_{a,0} = 0.01$, with a depreciation rate of $\delta_a = 0.05$. For the satellite's ISTC, calibrated values are $g_{q,0} = 0.03$ and $\delta_q = 0.05$. The number of satellites per launch is fixed to $\eta = 10$, given the average number of payloads per rocket in the last years. Finally, the conversion parameter is calibrated by dividing the initial number of satellites (rounded to 8,500) and the value of satellites, measured in output units, resulting in a value of 383,090.

4.3 Calibration of Physical Parameters

The model's physical parameters (see Table 1) have been calibrated to match the evolution of orbital objects for the period 1967–2023. Projections obtained using different models (Lewis 2020) for debris proliferation, such as the LEO-to-GEO Environment Debris Model (LEGEND), have estimated amounts of around 36,500 pieces of debris larger than 10 cm diameter, 1,000,000 objects between 1 cm and 10 cm, and over 130,000,000 fragments between 1 mm and 1 cm. The destruction power of debris smaller than 1 cm is estimated to be low and non-fatal in a collision with a representative satellite. However, such debris can cause severe damage to critical systems, reducing functionality and lifespan and even disabling small satellites. However, debris larger than 1 cm is potentially catastrophic due to the high speed of an impact. Hence, the model parameters are calibrated considering the estimated number of debris pieces larger than 1 cm.

The debris decay rate (δ_s) is a key parameter of the model. The decay rate of debris depends on several factors, including the altitude, mass, area, solar radio flux, circularity of the orbit, and geomagnetic index. The most crucial factor is the altitude due to the atmospheric drag. The Agency (1999) estimated that the lifetime of space objects varies from 1 day at 200 km, 1 month at 300 km, 1 year at 400 km, 10 years at 500 km, 100 years at 700 km, and 1000 years at 900 km (King-Hele 1987). On the other hand, debris distribution as a function of altitude is not homogeneous. The spatial density of debris shows a large concentration in the range of 700–900 km (NASA 2020). For calibrating this parameter we take into account the current distribution of objects in orbit, where most activity is concentrated at an altitude of 550 due to the Starlink satellite constellation, and that Starlink sub-constellations are planned for 340 km and 1,200 km. Also, it is important to take into account that the OneWeb satellite constellation (currently there are 658 satellites in this constellation) orbit at an altitude of 1,200 km, where the lifetime of debris is of thousands of years. In the literature, we find alternative calibrated values for the debris decay rate. For instance, Nozawa et al. (2023) use a value of 0.0067, taken from Bongers and Torres (2023), a value similar to the one estimated by Lewis et al. (2009) of 0.0062 in the Fast Debris Evolution (FADE) model, whereas Rao and Rondina (2025) consider a value of 0.074. Lafleur (2011) calculates an average debris decay rate for objects in LEO (up to 2,000 km) using the ballistic coefficient for a value of 1.8 kg/m^2 as an approximate value for fragments, from which he calculates the drag coefficient for the solar-maximum and the solar-minimum conditions. Values are weighted by the distribution of objects at different orbit altitudes. At the solar-maximum conditions, the average lifetime of debris fragment is of 46.9 years (a decay rate of 0.021), whereas at the solar-minimum conditions, the average lifetime of debris fragments is of 332.8 years (a decay rate of 0.003), resulting in a mean value for the decay rate of 0.012 for LEO. Based on that information, in the baseline model we use a value of $\delta_d = 0.01$, that is, a debris decay rate of 1% per year, which approximately corresponds to an average orbit of about 750 km.

A second key parameter is the risk of collision (θ). Several collisions have been reported in the history of activity in outer space. Collisions can occur between pieces of debris or between debris and operational satellites. A risk of collision between operating satellites also exists. However, in some cases, they can be avoided by maneuvering, although many satellites have slow or no maneuvering capability. Krisko (2007) estimated an average number of catastrophic collisions (with a target and impactor larger than 10 cm) of 0.9. In contrast, the estimation from the DAMAGE model (Lewis et al. 2009) is 1.5, both for the period 1957–2006. Farinella and Cordelli (1991) estimated a value of $\theta = 3 \times 10^{-10}$ for an estimated quantity of debris of 50,000. This results in 0.2 satellites destroyed per year, given a probability of collision ($\theta \times 50,000$) of 1.5×10^{-5}. We only consider debris larger than 1 cm. Debris smaller than 1 cm is assumed not to cause fatal damage in case of collision. Given the number of incidents observed during the last years, we assume one collision per year. Given a total number of potentially hazardous pieces of debris of about 1,000,000, this results in a value for the probability of collision parameter of $\theta = 1.25 \times 10^{-10}$.

It was quite common during the first stages of space conquest when satellites ran out of fuel and could not be placed in graveyard orbits. Given their mass, abandoned satellites represent a threat. Indeed, one of the most harmful incidents was the collision of Kosmos 2251 with Iridium 33 in February 2009. However, the number of abandoned satellites is relatively small in comparison to other forms of debris. New international standards for spacefaring countries and firms require adding reserve fuel for de-orbiting maneuvers. As a result, it is expected that the number of derelict satellites abandoned in orbit will tend to zero over time. The fraction of abandoned satellites (χ) is calibrated to match the number of derelict satellites that remain in orbit and is fixed to $\chi = 0.35$. Using a similar procedure, the fraction of body rockets abandoned in orbit is fixed to $\varphi = 0.80$.[5] The fraction of dead satellites breakups (δ_w) is fixed to be 0.002, whereas the fraction of rocket bodies breakups (δ_z) is fixed to be 0.001.

The remaining parameters are the number of pieces of debris from derelict satellites breakups (σ), the number of debris from rocket bodies breakups (ρ), the number of piece of debris per launch (ω) and the number of fragments per operational satellite collision (γ), fragments per derelict satellite collision (ε), and the fragments per rocket body collision (ν). For the calibration of these six parameters, we have mainly used the NASA breakups database by Anz-Meador et al. (2022). This report collects on-orbit breakups, collisions, and other anomalous events by satellites, rocket bodies, and ullage motors up to 15 April 2022, the cause of the fragmentation, and the number of cataloged debris. In this report, there are a total of 268 fragmentation and 87 anomalous events. The distribution of fragmentation events is as follow: 6 collisions with debris, 83 rocket bodies breakups, 7 anti-satellite tests, 53 ullage motors breakups, 51 satellite self-destruction, and 68 satellites and other spacecraft fragmentation events by unknown causes.

For the calibration of the amount of debris produced by derelict satellites breakups σ, in the NASAs breakups database (Anz-Meador et al. 2022) there is a total of 47 satellite breakups until 2022 (although one was an operational satellite), excluding deliberate destruction events by anti-satellite tests or by self-destruction with an explosive charges. These breakups are mainly due to unknown causes (36 out of 47). In other cases, the detected cause is battery explosion (9 confirmed cases), and due to propulsion (2 confirmed cases). The number of cataloged debris produced by these satellite breakups is of 2,289, an average of 49.3 cataloged fragments per event. Excluding the breakup of an operational satellite, the average cataloged fragments per derelict satellite breakup event is 44.6. For the calibration of the number of fragments per rocket body breakup (ρ), as for the previous parameter, we use the information in (Anz-Meador et al. 2022) about breakup events of rocket bodies and the number of debris produced. This database contains a total of 83 rocket body breakups, producing a total of 8,315 pieces of cataloged debris, an average of 100.2 pieces of debris per rocket body breakup. Therefore, we fix $\rho = 100.2$.

The parameter ω includes parts discarded during satellite deployment into a target orbit. Lewis et al. (2009) estimated that an average of 2.75 intact objects are added to the space environment per launch. Here, it is assumed that the number of debris larger than 10 cm per launch is 4. According to the NASAs breakups database (Anz-Meador et al. 2022), the number of collisions registered has been of 6, producing a total of 2,430 cataloged debris (an average of 347 pieces), although there is a total of 67 unknown breakups events producing a total of 3,436 cataloged debris (an average of 51 pieces per event). In the DISCOS database, the number of collisions between operational satellites and piece of debris is 5, and the

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[5] Historically, not all launches have resulted in upper states of rocket launch systems remaining in orbit. During the period 1981–2011 the number of rocket bodies was lower than the number of launches due to the NASA Space Shuttle program, a series of reusable launch vehicles. NASA's space shuttle fleet flew 135 missions (the Soviet Union Buran shuttle only completed one flight). Although the Space Shuttle program ends in 2011, currently there is a number of initiatives by private firms to reduce costs by developing reusable launch systems. For example, the SpaceX Starship is not yet operational but has completed four orbital test flights. On the other hand, the fraction of rockets bodied abandoned in orbit has declined in the last years due to the fact that some spacefaring operators conduct systematical upper stages disposal. This is the case of the SpaceX Falcon-9 vehicles (a two-stage rocket), which the stage-2 of the vehicle is normally deorbited after payloads have been released. Jonathan McDowell's annual reports on Space Activities gives detail information about the disposal of launch vehicles upper stages McDowell (2024).

average number of cataloged fragments is of 483.6. Johnson et al. (2001) used the NASA Breakup model EVOLVE 4.0 to estimate the number of new fragments from an explosion: 238 larger than 10 cm and 9,509 larger than 1 cm. Johnson et al. (2001) estimated that the number of fragments larger than 10 cm generated by an explosion is 50 and that an average of 2.75 intact objects are added to the environment per launch. Therefore, we assume that around 100 pieces of debris larger than 10 cm are generated per collision. Farinella and Cordelli (1991) assume an average of two unintentional explosions per year, each creating a few thousand fragments of mass greater than 1 gram, producing 70 new pieces of debris larger than 10 cm, resulting in a total number of new pieces of debris of 2,059 larger than 1 cm.[6] From this information we assume $\gamma = 100$.

Finally, for calibrating the parameters ε and ν, we assume that the number of debris produced by collision of derelict satellites and rocket rocket bodies is the same as for operational satellites. Derelict satellites have the same characteristics as operational satellites. Therefore, in case of collision, they will be fragmented in a way similar to that of the rest of the operational satellites. For the number of fragments per rocket body collision, we follow Kessler et al. (2010) and assume that they are equal to a payload collision, that is, $\nu = 100$. Given the differences in mass and size between rocket bodies and satellites, we could expect a different fragmentation behavior in the event of a collision.[7] The source for the calibration of this parameter is Anz-Meador et al. (2022). However, there is only one collision between a rocket body (DMSP-5B-F5 Thor-Burner 2A rocket) and other debris on January 2005, producing 5 cataloged debris. Another collision was deliberate (the collision of USA-19 with the upper stage of USA-19), with the fragmentation of USA-19 in 13 cataloged debris and the fragmentation of the rocket body in 5 cataloged debris. However, we consider that this evidence is not representative given the size and mass of rocket bodies. As no additional information is available, we assume that the number of debris produced by the collision of a rocket body with other piece of debris is equal to the one produced by the collision of a satellite.

5 Policy Experiments

This section details the various policy experiments conducted using the calibrated DISE model. We take the current situation of no active debris removal (ADR) policies and voluntary debris mitigation guidelines as the baseline scenario. As alternative scenarios, we consider a compulsory derelict satellites de-orbiting policy starting in 2030, a de-orbiting policy

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[6] Only 3.54% of the estimated pieces of debris are larger than 10 cm. The remaining 96.36% are between 1 cm and 10 cm. If an explosion produces 70 pieces of debris larger than 10 cm, the total number of pieces larger than 1 cm is estimated to be 70/0.034 = 2,059.

[7] Kessler et al. (2010) indicate that whereas a number of tests have been conducted to understand the size distribution from the collision of a payload, none have been conducted on rocket bodies, and the standard assumption in breakups models is that payloads and rocket bodies fragment under identical conditions and produce identical fragment distribution. However, as these authors note, the large tanks on rocket bodies may not absorb all the energy from a collision. Alternatively, they may dissipate the energy across the opposite tank wall, functioning similarly to a Whipple shield. Consequently, it remains uncertain whether a rocket body collision would generate more or fewer fragments than a satellite collision. We conducted a sensitivity analysis using a range of values from 50 to 200 for the number of fragments resulting from rocket body collisions. The trajectories of the variables exhibit similar patterns, and the conclusions remain consistent, although the rate of debris accumulation increases as the parameter value rises.

for both dereclit satellies and upper stages rocket bodies, debris-free (reusable) launch systems, a combination of de-orbiting policy and debris-free launch vehicles, and a scenario with no collisions. In addition, we also simulate a scenario with no debris to measure the cost of orbital pollution as foregone global output. We assume that mandatory debris mitigation policies are costless, and hence, all results correspond to the best-case scenario. In the context of a partial-optimal growth model, the introduction of abatement costs would simply result in an equivalent reduction in consumption, without affecting other variables.[8]

5.1 Baseline: Laissez-Faire

This represents the current situation, where no action is taken to mitigate debris. Considering outer space as an international common resource and the difficulties of a global agreement to mitigate debris generation and reduce the stock of orbital debris, this scenario is highly plausible. In this baseline scenario, households and firms consider the stock of orbital debris as given, with no internalization of the social externality cost by any authority. Space-faring agents simply adapt to the space environment and take the amount of debris as given. National Space Agencies and the United Nations have proposed debris mitigation guidelines, but they are not binding. This scenario represents an environment where the current policy is maintained without changes in the future.

5.2 Derelict Satellites de-Orbiting Policy

One source of orbital debris is derelict end-of-life satellites and the upper stages of rocket bodies. These large debris pieces are tracked by surveillance systems. However, they pose an additional threat as they can break apart, generating thousands of fragments. Debris mitigation guidelines recommend de-orbiting non-operational satellites to reduce this risk. There is significant international interest in addressing this issue, as reflected in the Inter-Agency Space Debris Coordination Committee (IADC) mitigation guidelines. These guidelines recommend the removal of space systems that interfere with the Low Earth Orbit (LEO) region no later than 25 years after the end of their mission. Although non-binding, these guidelines emphasize the need for new spacecraft to incorporate robust and reliable de-orbiting systems. From a technical perspective, disposing of end-of-life satellites is relatively straightforward: active satellites retain propellant, allowing them to maneuver to disposal altitudes. In this scenario, we consider a policy that mandates the de-orbiting of derelict satellites starting in 2030. To simulate this policy, we assume $\chi = 0$, meaning that satellites are removed from orbit at the end of their operational life, ultimately reducing the number of derelict satellites to zero over time.

5.3 All Intact Objects de-Orbiting Policy

Mitigation guidelines focus not only on the disposal of derelict satellites but also on the disposal of upper-stage rocket bodies. In this scenario, we consider the de-orbiting of both derelict satellites and rocket bodies once they have completed their missions. For upper-stage

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[8] Note that a centralized economy cannot be analyzed within this partial-equilibrium theoretical framework, as the saving rate is predetermined. Consequently, in no scenario is the negative externality fully internalized, nor is the debris mitigation policy optimal.

rocket bodies, similar disposal procedures to those used for derelict satellites are already being implemented by launch operators such as SpaceX with the Falcon-9. In the case of the Falcon-9s second stage, a de-orbit burn is performed after mission completion to lower its altitude until it burns up in the atmosphere. For a detailed account of upper-stage rocket launches and disposal procedures, see Jonathan McDowell's Space Activity reports from 2019 to 2024, which describe the numbers and types of upper-stage rocket launches where disposal measures were implemented after payload deployment. In fact, in September 2023, the Federal Aviation Administration (FAA) proposed a new rule for upper-stage disposal, requiring operators either to conduct controlled atmospheric reentries or to move upper stages to higher disposal orbits.

In this scenario, we assume mandatory de-orbiting of end-of-life satellites and rocket bodies immediately after payload deployment. The Inter-Agency Space Debris Coordination Committee (IADC) and various national space agencies have established a 25-year post-mission disposal rule, aiming to reduce orbital debris by requiring the removal of objects in Low Earth Orbit (LEO) or the relocation of those in Geosynchronous Orbit (GEO) to a higher 'graveyard' orbit. Rao et al. (2023) analyze a 5-year disposal timeframe and compare it to the standard 25-year guideline. Here, we take a more aggressive approach by simulating a 1-year post-mission disposal rule starting in 2030. Under this scenario, we assume $\chi = 0$ for the de-orbiting of end-of-life satellites and $\varphi = 0$ for the de-orbiting of upper-stage rocket bodies. This policy results in both derelict satellites and rocket bodies gradually decreasing to zero over time.

5.4 Debris-Free Launch Systems

Next, we consider a scenario where the technology allows the development of debris-free launching systems. In this scenario, all the launch vehicles' stages are recovered for reuse or, in case they are not reused, they are de-orbited after inserting the payload into orbit and they are burned up into the atmosphere, or moved to a disposal orbit,).[9] and payload deployment does not cause new debris. Debris-free launch systems have been developed in the past. For instance, NASAs Space Shuttles return to Earth and land as planes after completing their mission. More recently, SpaceX has developed reusable launch vehicles such as the Falcon-9. The company is also designing and developing massive rockets to deploy satellites into orbit like a Pez dispenser, avoiding debris generation, such as payload fairing parts. To simulate this scenario, we set $\omega = 0$ and $\varphi = 0$. The use of debris-free launch systems has two effects. First, launch vehicles, including rocket bodies, are recovered or burned up in the atmosphere and hence, the number of rocket bodies in orbit tends to zero over time. Second, launches is not a source of debris generation anymore.

Currently, there are no entirely debris-free launch systems, except for the SpaceX Starship. Between 1981 and 2011, the Space Shuttle operated as a debris-free launch system, though it was not fully reusable. However, due to the high cost of rockets, some launch companies are currently pursuing fully reusable launch vehicles.[10]

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[9] This is the standard procedure for launch systems such as the SpaceX Falcon-9, where the second stage is disposed of after completing its mission and burns up in the atmosphere (McDowell 2024).

[10] Initially, SpaceX also planned to reuse the second stage of the Falcon-9. The second-stage engine was designed to be reusable, but the additional mass required for a heat shield, low-powered landing engines, and other landing mechanisms made full reusability impractical. Ultimately, SpaceX abandoned the project, not

5.5 Combination of de-Orbiting and Debris-Free Launch Systems

This scenario simultaneously considers a compulsory de-orbiting policy, for both dereclit satellites and rocket bodies, with debris-free launch systems. To simulate this scenario, we set $\chi = \omega = \varphi = 0$. The interest in simulating this scenario is to assess the future evolution of orbital debris excluding any primary source. The only remaining sources of orbital debris production are collisions and breakups.

5.6 No Collision

This scenario assumes that all satellites and other types of spacecraft have maneuvering capabilities. Tracking systems can alert satellite operators for possible collisions, and satellite operators can perform collision-avoiding maneuvers. Note that tracking orbital debris and collision-avoiding maneuvers are costly. To simulate this scenario, we simply assume that the number of operational satellites destroyed by collision is zero ($X_t = 0$), and the only collisions are between derelict satellites and rocket bodies with each other and other fragments.

Tracking and collision avoidance procedures can be costly. The literature identifies three main costs associated with collision avoidance: tracking, fuel consumption, and service interruptions. Locke et al. (2024) provide estimates for these costs. However, there are limitations to conducting collision avoidance maneuvers, particularly due to the difficulty of tracking small debris pieces that are still large enough to cause severe consequences in the event of a collision (Lewis and Skelton 2024). Nevertheless, technological advancements are expected to improve the tracking of smaller debris and enable spacecraft to develop onboard conjunction detection and automatic orbit correction systems. The objective of this scenario is to assess the implications of the endogenous generation of debris resulting from collisions of operational satellites and their impact on the accumulation of satellites.

5.7 Clean Space Environment

Finally, we simulated the model without any debris, representing a fictitious scenario of a clean space environment. This scenario helps to measure the costs associated with orbital debris by serving as a point of comparison with all other scenarios. In this scenario, we solve the model by assuming that debris is zero ($D_t = 0$). As a result, the rental rates of the two types of capital are equal to their marginal productivity, reflecting an environment where investment decisions in the two types of capital are solely determined by their relative marginal productivities. Thus, there are no limitations on economic growth imposed by the space environment and the "economic" Kessler syndrome is ruled out, as this scenario represents a world without space environmental externalities. Although this scenario is completely unrealistic, it would be useful for quantifying the cost of the debris externality.

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only due to cost but also because of the significant performance penalty it imposed. Other spacefaring companies, such as Stoke Space, are also pursuing the development of fully reusable launch vehicles.

6 Results

The simulation of the model is carried out annually for the next 200 years, starting in 2024, with the initial values of the variables corresponding to the year 2023.[11] The results can be compared with those obtained by Kessler et al. (2010), Adilov et al. (2020), Nozawa et al. (2023), Rao et al. (2023), and Rao and Rao et al. (2023). Adilov et al. (2020) do not use any economic model and instead assume that by the year 2235 the probability of collision will be one, and that by the year 2100 the number of objects larger than 10 cm will be above 50,000 with no interventions. Nozawa et al. (2023) show that if debris remediation strategies are not implemented, orbital debris will have a negative impact of approximately 1.95% of global GDP over 200 years. In Nozawa et al. (2023), the Kessler threshold is fixed at about 350,000 pieces of debris larger than 10 cm, which, depending on the mitigation intervention, will be reached between the years 2080 and 2140. Rao and Rondina (2025) study the dynamics of Kessler syndrome defined as a state from which debris stock diverges to infinity, predicting that such catastrophic event can emerge between the years 2040 and 2184.

Simuations from DISE indicates that, for the next 100 years, economic activity and the space environment will be fairly similar across all scenarios, with few differences. The reason is that the cost of orbital debris remains low despite increasing economic and space activity. These results indicate that orbital debris is a long-term issue. However, the situation dramatically changes from the year 2150 and onwards, where the accumulation of debris and satellites leads to a rapid growth in the probability of collision, increasing the rate of debris generation.

Fig. 1 plots the number of satellites, launches, and new satellite losses in alternative scenarios. For the non-collision scenario, the number of satellites increases steadily over the whole period, as collision risk is assumed to be zero. In contrast, in the other scenarios, the number of satellites in orbit reaches a maximum and then decreases. This result implies that the cost of losing satellite assets increases over time, reducing investment returns on satellites. In the non-intervention scenario, the maximum number of satellites is around 125,000. We define this tipping point as an "economic" Kessler syndrome, as the stock of satellites begins to decreases due to the accumulation of debris although economic growth is positive and the stock of Earth's capital continues to accumulate. This figure is not too large, given the expected economic growth and the satellite's ISTC during the simulation horizon. In fact, the satellite population would be less than 100,000 at the end of the simulation horizon if no debris mitigation intervention is done.

Two important findings are worth noting. First, de-orbiting dead satellites, as well as de-orbiting both derelict satellites and rocket bodies, proves to be a more effective mitigation strategy than implementing debris-free launch systems. This advantage primarily stems from the long-term accumulation of satellites and the risk posed by derelict satellites, which can collide with other objects or break apart. Consequently, enforcing a policy that mandates the de-orbiting of end-of-life satellites and rocket bodies within a year would be more beneficial in the long run than focusing on the development of debris-free launch technologies. However, these two measures alone are insufficient to significantly curb space pollution over time. As a result, the number of optimal satellites eventually reaches a tipping

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[11] A sensitivity analysis, using alternative values for the exogenous sources of growth and a range of values for some key parameters, has been carried out, but the main results remain. The trajectories of the variables show similar paths and only the timing differs.

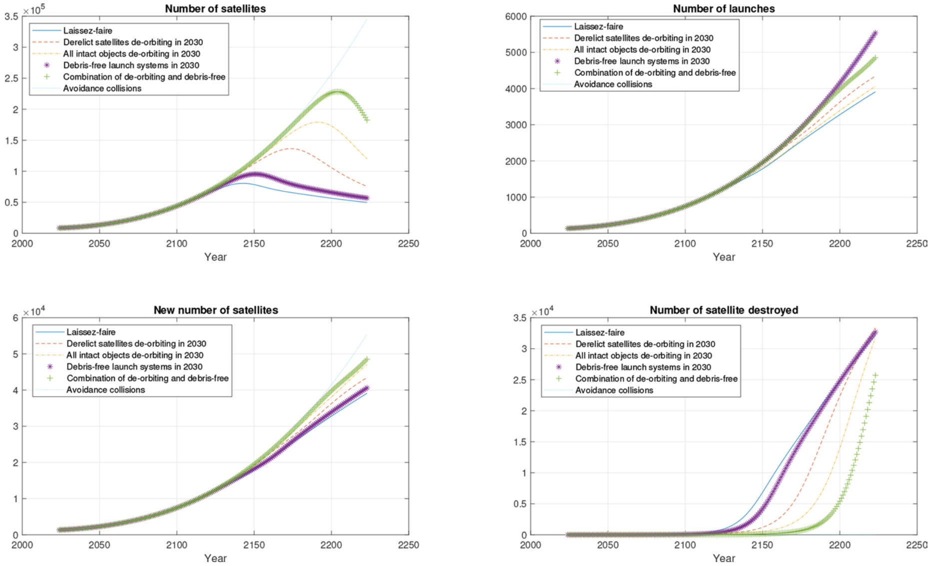

Fig. 1 Trajectories for satellite stocks, launches, new satellites, and satellites destroyed by collisions

point, leading to an "economic" Kessler syndrome, where satellite numbers begin to decline despite continued capital accumulation on Earth and sustained economic growth. Second, even combining these mitigation strategies is not enough to prevent the tipping point in satellite stock. Therefore, relying solely on a compulsory de-orbiting policy and debris-free launch systems is insufficient to curb the spread of orbital debris to a level where the optimal number of satellites in orbit remains stable.

The bottom-right panel shows the number of satellites destroyed by collisions. While initially small, this number gradually increases until the year 2150. After that, collisions rise sharply due to the accumulation of both orbital debris and satellites. A striking finding is that, in the long run, the number of satellites destroyed in the debris-free launch scenario is similar to that in the non-intervention scenario. Implementing de-orbiting policies for derelict satellites, as well as for both derelict satellites and rocket bodies, delays the rise in satellite destruction by a few decades but proves ineffective in the long run. Although the combination of de-orbiting policies and debris-free launch systems significantly reduces collisions along the trajectory, it does not prevent long-term increases.

Figure 2 plots the number of objects in orbit, considering only fragments larger than 10 cm. The number of fragments increases exponentially at the end of the simulation period in all scenarios, including the non-collision scenario. This result is very relevant, as the model simulation indicates that one of the future primary sources of debris production would be increased collisions among intact objects (derelict satellites and rocket bodies) with debris. During the first 100 years (up to 2125), the dynamics of orbital debris are relatively similar across the different scenarios. However, once the number of debris reaches a specific value, collisions are large enough to drive up debris growth. The combination of de-orbiting policy and debris-free launch vehicle technology only delayed reaching a certain number of fragments for a few decades. For the de-orbiting policy, the number of derelict satellites and rocket bodies in orbit goes to zero, but the effect on the total accumulation of

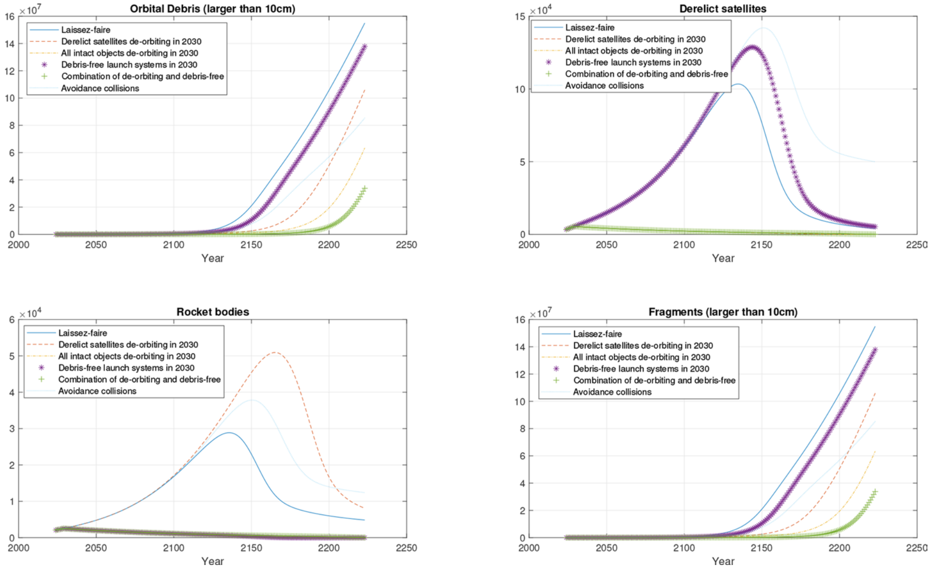

Fig. 2 Number of objects in orbit: derelict satellites, rocket bodies and fragments

orbital debris is small compare to the non-intervention scenario. Also, the number of rocket bodies in the debris-free launch systems scenario tends to zero, but the trajectory of total orbital debris is similar to that generated by the de-orbiting policy. Furthermore, the impact on fragment proliferation for these two scenarios or their combination is already limited in the long-run, only delaying the accumulation of pollution in space by a few decades compared to the laissez-faire scenario.

In summary, we find that while mandatory de-orbiting policies and debris-free launch systems can delay the exponential growth of orbital debris, they do not prevent it. Even in the absence of collisions, the accumulation of derelict satellites and rocket bodies continues to contribute to debris generation, albeit at a slower rate. This finding highlights that, over time, collisions become the primary source of debris production. Even if the main sources of debris generation are eliminated, the growing number of satellites and collisions ultimately lead to an unsustainable trajectory for orbital debris. Therefore, improved collision tracking systems and advanced collision-avoidance technologies will be essential in preventing an uncontrollable space environment.

Figure 3 plots the trajectories for the main economic variables: output, value of the stock Earth capital, value of the stock of satellites in orbit, and the cost (measured as output units) of destroyed satellites by collisions. We obtain three important findings. First, output differences across scenarios are minimal, given the relatively low value of the space economy compared to the rest of the economy. Similar behavior is observed for the stock of capital on Earth, which is not too sensitive to the situation in space. It is important to note that simulations are done using a production function with constant output elasticities with respect to Earth's capital and satellites. Data show that the stock of satellites and the production of services from space are minimal in the economy. In the baseline calibration of the model, the stock of space capital and the output-satellite elasticity technological parameter are already small compared to Earth capital stock. The elasticity of output for the stock of satellites is a

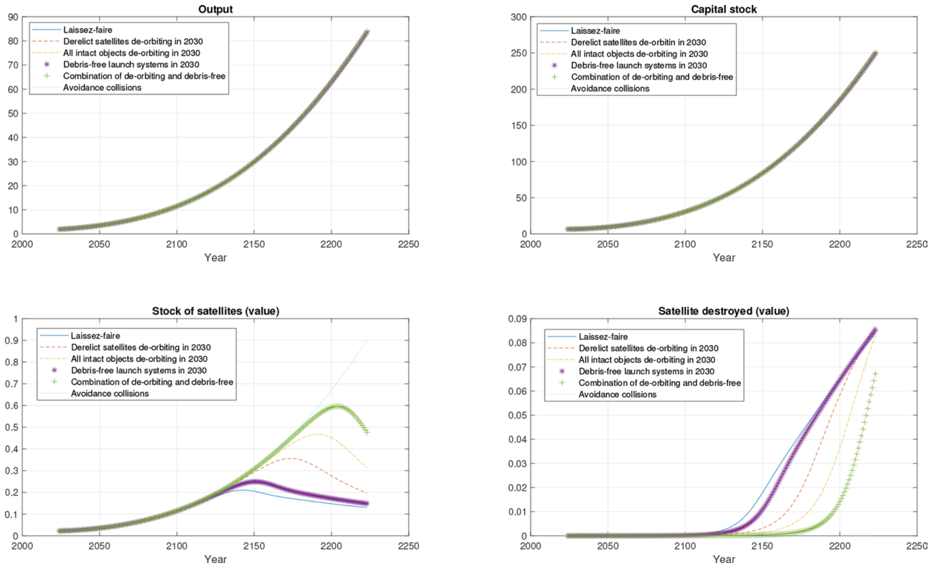

Fig. 3 Output, capital stock, stock of satellites and value of satellites destroyed by collision

minimal number (0.0021) for all the simulation horizons, causing variations in the stock of satellites in orbit that have a negligible effect on aggregate output. However, this parameter does not need to be constant over the simulation period, as the number of satellite services is expected to increase in the future. Despite the initial higher growth of the space sector compared to the Earth sector, driven by satellite investment-specific technological progress, the accumulation of orbital debris is an obstacle to further expansion of the space sector. Second, the value of satellite assets increases at a similar rate to output in the non-collision scenario. However, in the other scenarios, the value of satellite assets declines between the year 2150 and the year 2170. Third, the value of satellite assets destroyed by collision at the end of the simulation horizon (year 2223) are similar across the laissez-faire, de-orbiting policy and debris-free launch vehicles scenarios. This result is very significant because the long-run effects of de-orbiting and debris-free launch technology, and even the combination of both measures, are limited to effectively controlling orbital debris growth in the long-run.

Figure 4 plots the difference in total output relative to the laissez-faire scenario. In all cases, we obtain positive gains as the negative impact of the debris externality is partially reduced by the alternative mitigation policies. As expected, the larger output gains are obtained for the non-collision scenario. At the end of the simulation horizon, the total output would be around 0.6% larger than in the laissez-faire scenario. This is a relatively high value given the small contribution of the space economy to total output in the aggregate production function for the World economy. Output gains from the other scenarios are much more modest and even reduced during the last years of the simulation horizon, given the negative impact of debris on the stock of satellites. For comparison, the output cost would be around 0.05% in the combination of de-orbiting and debris-free launch scenarios, around 0.05% in the derelict satellites and rocket bodies de-orbiting scenario, and around 0.2% in the derelict satellites de-orbiting scenario.

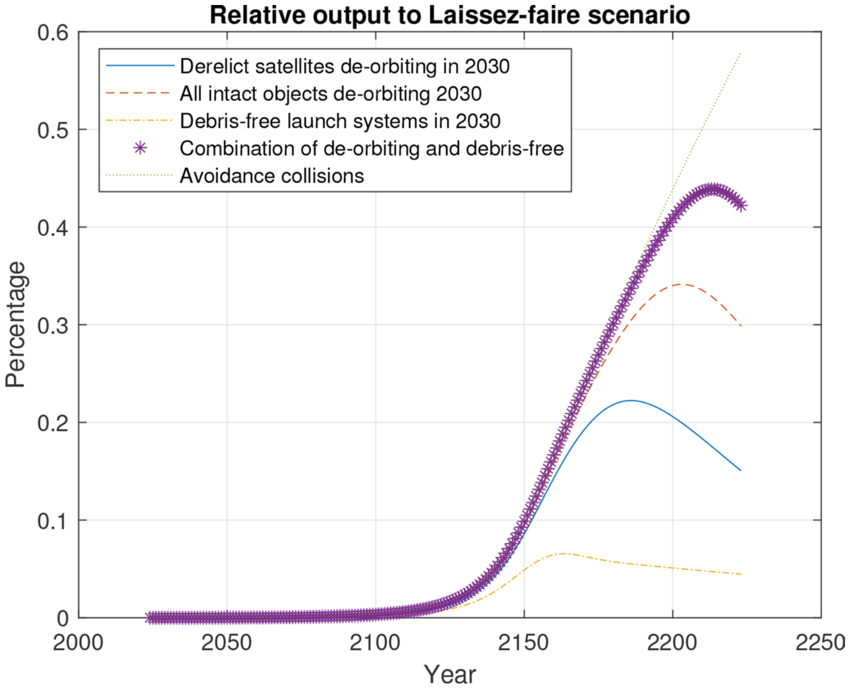

Fig. 4 Output gains with respect to the laissez-faire scenario

Similarly, Figure 5 calculates output losses for an ideal scenario of no orbital debris (clean space environment) to assess the output cost of orbital debris. For the laissez-faire scenario, the output cost would reach about 0.6% in the next 200 years. Output cost is lower for the other scenarios but also significant. For the combination of de-orbiting policy and the debris-free launch scenarios, the loss is around 1.5%. Therefore, even if the space sector remains small compared to the Earth sector, output losses caused by the accumulation of orbital debris are significant.

Fig. 6 plots the cost of collisions (measured as the value of destroyed satellites over total output). This is a direct estimation of damages, showing an S-shape over the simulation horizon. De-orbiting policies and debris-free launch technology limit the damage produced in the laissez-faire scenario. However, at the end of the simulation horizon, damages are very similar for these scenarios (around 0.1% of output in the de-orbiting, debris-free launch systems, and no intervention, and around 0.8% in the combination of de-orbiting and debris-free launch systems). De-orbiting policies and debris-free launch technologies positively impact the short run, reducing debris growth, but simply produce a delay of damages, with limited effects in the long-run. Lee et al. (2024) estimates the loss of value of satellites due to orbital debris for South Korea using a contingent valuation approach, estimating a willingness to pay by households of $16.4. Lee et al. (2024) and Lee et al. (2024) define the cost of orbital debris as the sum of the costs related to satellites (including damages to satellites, the cost of avoiding collisions, and the cost of disruption of services), the impact on space stations, and the impact on Earth.

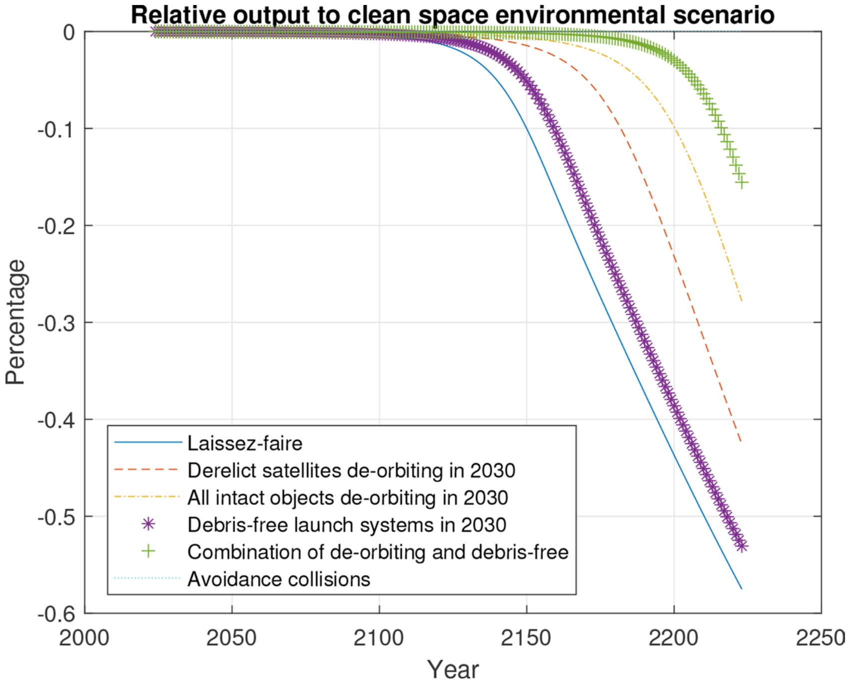

Fig. 5 Output losses with respect to a space-clean environment

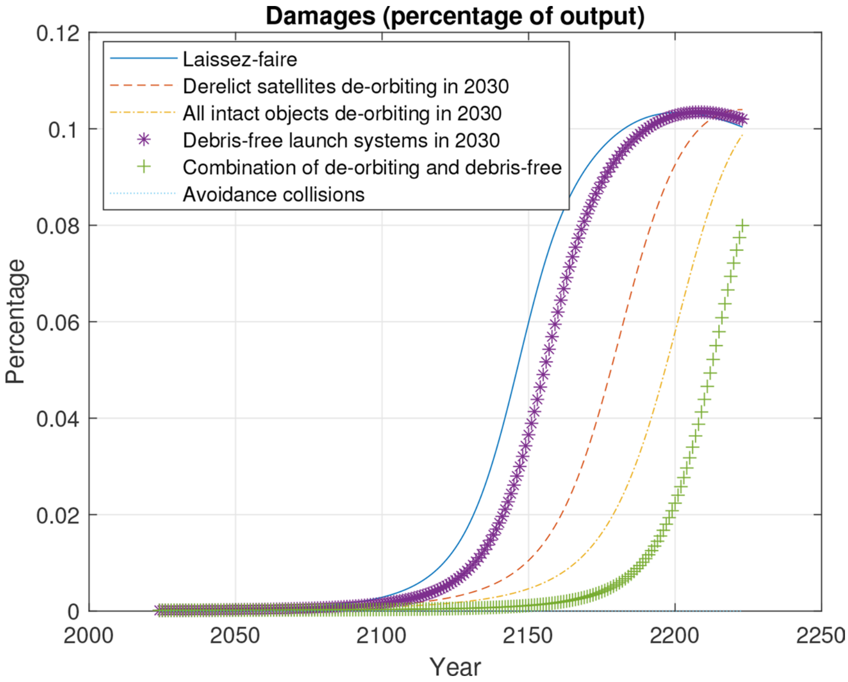

Fig. 6 Output cost of collisions

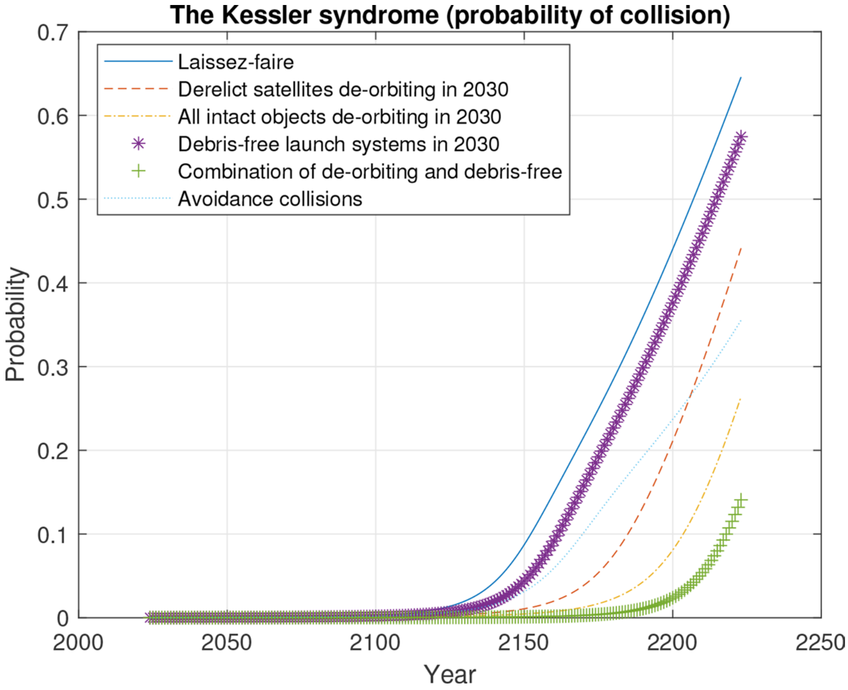

Fig. 7 The Kessler syndrome: probability of collision for satellite

Finally, Fig. 7 plots the probability of collision for a satellite (θD_t). This represents how close the space environment is to the Kessler syndrome as defined by Adilov et al. (2018), where the probability of collision is one. Adilov et al. (2018) indicate that a collision probability of one would represent the physical Kessler syndrome and would take place later than the economic Kessler syndrome. At the end of the simulation horizon, the collision probability for the laissez-faire scenario is above 0.6, still far from a situation where the space is unusable. Nevertheless, as shown in previous figures, in any scenario with collisions, the economic Kessler syndrome (a threshold from which the number of satellites starts to decrease) is reached before the end of the simulation horizon. It is worth noting that in our baseline simulation, the physical Kessler syndrome as defined by Adilov et al. (2018) is not reached during the simulation horizon (200 years). However, for a similar simulation horizon, the Kessler syndrome (a collision probability of one and the destruction of all satellites within a year) appears in Adilov et al. (2020) and in Nozawa et al. (2023).[12]

7 Conclusions

This paper presents an integrated assessment model (IAM) for the space environment as a theoretical framework for studying alternative policies to mitigate pollution problems in space. The environmental negative externality arising in space consists of orbital debris.

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[12] The spatial dimension would be a key aspect in the evaluation of the Kessler syndrome. However, this spatial dimension is missing in our aggregate model.

Damage to space equipment comes mainly from collisions of orbital debris with operational satellites. Like climate change IAMs, the model consists of two sub-models: an economy model based on the neoclassical growth model and a simplified orbital debris evolutionary model. The economic model is a partial optimal growth model; firms seek profit maximization, and households make optimal decisions about the portfolio of capital assets on Earth and in space, subject to an exogenously given saving rate.

The model simulation is carried out annually for the next 200 years, starting from 2024, with the initial values of the variables corresponding to 2023. It considers alternative scenarios, including laissez-faire, de-orbiting policy of derelict satellites and rocket bodies, debris-free launch systems, and no-collision. Furthermore, the growth model is simulated for a fictitious space environment with no debris to measure the cost of orbital debris. The model considers two exogenous sources of growth: neutral technological change and investment-specific technological change to satellites.

From the analysis, we obtain four main findings. First, as the number of debris increases, so does the number of collisions, resulting in a decreasing optimal number of satellites, except for the non-collision scenario. The rise in the probability of collisions reduces the returns on investment in space capital, which in turns reduce the optimal number of satellites. Second, as time passes, the main source of debris generation changes from the primary sources (launches) to collisions with operational satellites, resulting from the accumulation of satellites and orbital debris, which increases the number of collisions. Third, we observe that the satellite stock begins to decrease before the probability of collision reaches one. We identify this tipping point with an "economic" Kessler syndrome, where the stock of satellites declines even with positive economic growth and accumulation of Earth's capital. Finally, the most important finding is that the implementation of de-orbiting policies, eliminating breakups of rocket bodies and derelict satellites, and the development of debris-free launch vehicles all contribute to the short-run mitigation of orbital debris. However, given the current level of orbital pollution, they have a limited positive effects on the space environment in the long-run, except in the non-collision scenario. The main conclusion from the results is that in the long-run, mitigation of orbital debris will depend on developing avoiding-collision technologies and implementing active debris removal (ADR) policies to clean the space environment.

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Data availability All data and codes used in this study are publicly available and can be accessed upon request.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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