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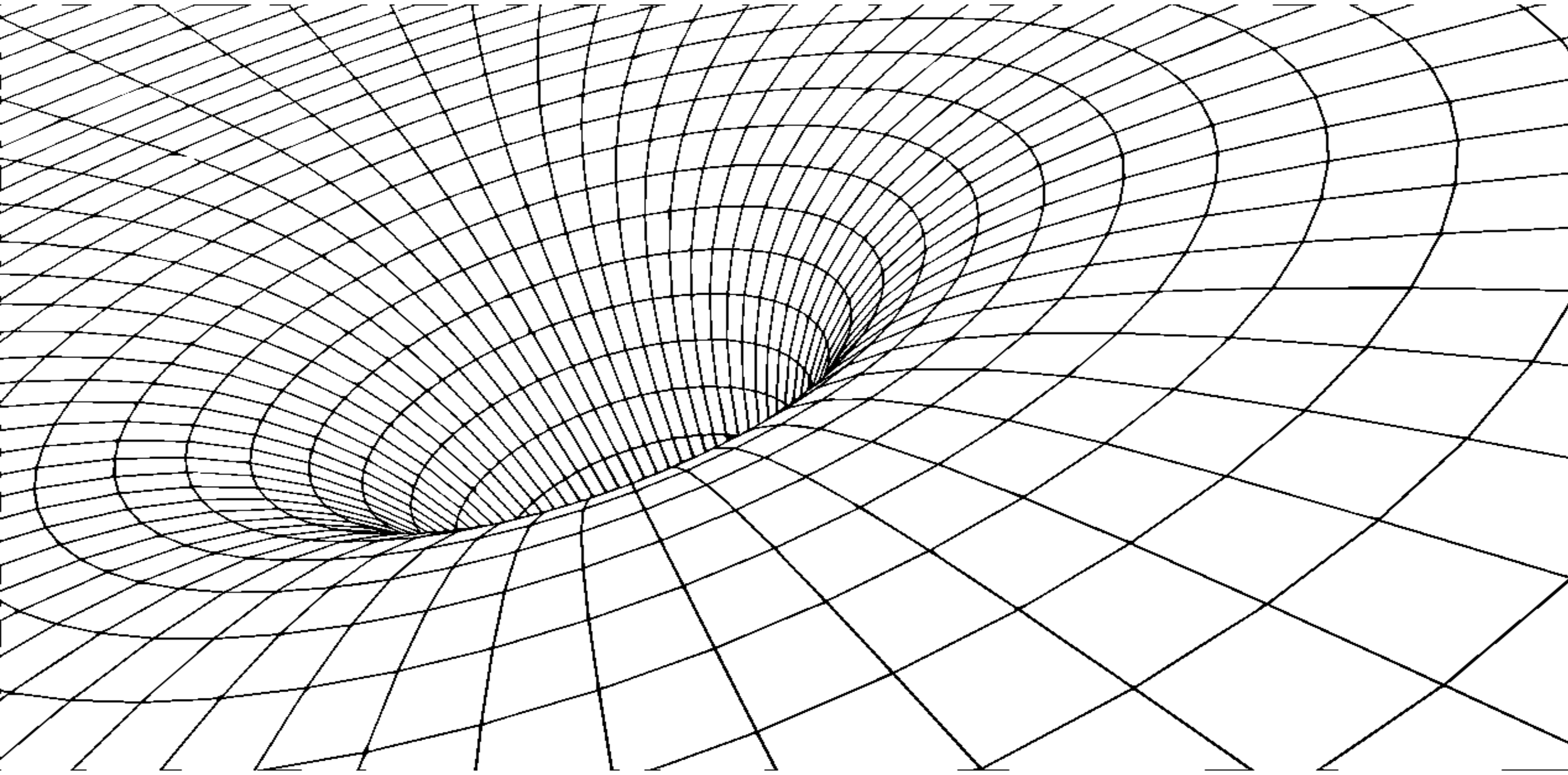

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DISE: A Dynamic Integrated Space-Economy Model for Orbital Debris Mitigation Policy Evaluation[⋆]

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Abstract

This paper presents the Dynamic Integrated Space-Economy (DISE) model, which is designed to study the economic implications of alternative policies aimed at mitigating 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). DISE is intended to calculate the cost of space debris and its impact on the global economy. The model is simulated for a 200-year period under different scenarios, including a clean space environment, laissez-faire, de-orbiting policy, debris-free launch systems, a combination of de-orbiting and debris-free launch vehicles, and collision avoidance.

Keywords: Outer space; Orbital debris; Satellites; Integrated Assesment 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 1. 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 is posing 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 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 that can collide with other satellites, leading to catastrophic results. Even collisions with small pieces of debris pose a serious risk due to the high speeds involved, impacting commercial, scientific, and defense activities in space. Various sources contribute to orbital debris, including parts of launch vehicles, upper stages 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), which describes a scenario of collisions among orbital debris in cascade.

The issue of orbital debris has gained attention from economists who are developing different models that combine an economic (micro) model with a physical model for orbital debris. These initial attempts to combine economic and space variables models include Adilov, Alexander and Cunningham (2015, 2018), 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. A number of papers focuses on the use of alternative policy instruments (i.e., taxes) for internalizing the social cost of orbital debris, such as Grzelka and Wagner (2019), Béal, Deschamps and Moulin (2020), Rouillon (2020), Rao, Burgess and Kaffine (2020), Adilov et al. (2020), Guyot and Rouillon (2022), and

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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.

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 us compliance with space debris mitigation guidelines, launch tax, and active debris removal policies). Rao and Letizia (2022) combine an econometric model of space activity with a debris environment model based on a Particle-in-a-Box (PIB) model. 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. Attempts to estimate the social cost of space debris for the Korean economy are Lee (2024), and Lee at al. (2024).

In recent studies, neoclassical growth models have been used to analyze human activity in outer space. Nozawa et al. (2023) developed a macroeconomic growth model that includes a satellite sector and considers 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 spillover 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 contributes to the literature by introducing an integrated assessment model (IAM) for the global economy and the outer space environment, specially designed for the evaluation of some non-active mitigation policies to handle with the problem raises by orbital debris. 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 component that offers information about the impact of those activities on the space environment. Building on the tradition of IAMs like the DICE model by Nordhaus (1992, 1993) 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.

The economic core of DISE is a two-inputs dynamic general equilibrium growth model that includes elements of outer space. In this model, physical capital is produced 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 also takes into account the externality caused by the buildup of orbital debris. This externality depends on current and past levels of debris, which also undergo a natural depreciation rate due to atmospheric drag.

The IAM model 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 utilizes a satellite tax to fund the ADR policy. In this paper, we develop a deterministic version of that model which includes exogenous 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; and 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 in which launch systems were free of debris and fully reusable, and a scenario in which no collisions occurred due to advance tracking and avoidance maneuverability. In addition, the study also looked at a scenario without space pollution to assess the cost of orbital debris.

Based on the simulations of the model, we made three main findings. Firstly, as the output increases, so does the number of satellite launches and the number of satellites in orbit, leading to a rise in orbital debris over time. This results in more collisions with operational satellites, causing a decrease in the optimal number of satellites in orbit, except in scenarios without collisions. Secondly, the primary sources of debris production change over time. Initially, launches and satellite breakups are the main sources of debris, but as the number of satellites in orbit grows, collisions between debris and operational satellites become the primary source. Policies such as de-orbiting, eliminating rocket body breakups and derelict satellites, and developing debris-free launch systems can help mitigate orbital debris in the short and medium run. However, in the long run, they have limited positive effects as a result of the current level of orbital pollution. Lastly, based on the model's baseline calibration, we found that the number of satellites begins to decline before the probability of collision reaches one (the Kessler syndrome, ensuring that all satellites in orbit are destroyed by collisions). This aligns with the findings of Adilov et al. (2018), indicating that the 'economic Kessler syndrome' occurs before the 'physical Kessler syndrome'.

The organization of 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 done 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. Similar to 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. In this model, "satellites" are considered an additional type of capital in addition to 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. 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 capital 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 the 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.

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 deorbiting 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 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 is a worldwide model which uses aggregate variables for economic variables (world output, total Earth's capital, etc.) and for 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. 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, with includes 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 satellites 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.[2] The law of motion for the stock of satellites considers an investment-specific technological change (ISTC) component, denoted by q_t, (see Greenwood et al., 1997).

Output growth depends on two sources of technological change: Neutral tecnological 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

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[2] 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.

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 number of new satellites per unit of investment is determined by the satellite's ISTC. A higher value of q_t corresponds to a greater number of new satellites per unit of investment, which can be interpreted as that the relative price of satellites investment is decreasing. In practical terms, a positive trend in q_t suggests decreasing satellite launch and manufacturing costs.

By substituting the above mappings into the restriction (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's important to consider the number of launches as an additional auxiliary variable because the primary source of debris emission is the launching process. Standard launching systems use rockets with several (three 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 altitude. Additionally, during the insertion phase, additional pieces of debris are generated, such as fairings. However, recent technological advancements in launching systems have introduced reusable vehicles that do not produce debris. The number of launches is distinct from the number of satellites placed into orbit, as technological advancements 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 satellite launches separately from the number of new satellites being deployed. In fact, over 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 decreasing size and weight of satellites. As a result, the number of satellites inserted into 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 the number of satellites per launch. From here, we can obtain the relationship between investment in satellites, 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 poses a threat to space equipment due to high-speed collisions. This paper specifically focuses on man-made space debris, as natural space pollution is rare and minimally poses a threat 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 is unlikely, but 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 one kilometer per second in low Earth orbit (LEO). Collisions of this debris with operational satellites and other spacecraft can lead to the loss of space equipment.

There are various methods in the literature for calculating the likelihood of collisions in space. We consider a simple damage function that relies on the amount of satellites and the quantity of orbital debris greater than 1 cm. The number of satellites destroyed in each time period as a result of collisions with debris, as proposed by Farinella and

Cordelli (1991), 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 representing the probability of collision and D_t is the number of orbital debris. According to the above expression, and ussing the mapping parameters, 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:

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

where we distinguish three types of debris: W_t represents the stock of dead satellites abandoned in orbit, B_t is the number of rocket bodies left 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.

2.4.3. Emissions (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 ESA (European Space Agency) 'About space debris' website, until December 2023 there have been over 640 breakups, explosions, collisions, or anomalous events leading to fragmentation.

The model addresses four main sources of debris resulting from collisions and launches. The first source of space debris is mission-related objects (MRO), which are 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 also generate another type of debris related to the launch vehicles 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 is given by the expression φL_t, where $0 < \varphi < 1$ represents the fraction of launches that generate this type of debris. We assume that this fraction is strictly less than one to account for the existence of reusable launch vehicles. 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 regulations 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 are collisions.

The movement of derelict satellites over time can be described by the following equation:

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

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. In the calibration of this parameter we use an average altitude. The number of debris produces by the breakup of derelict satellites is given by $\sigma\delta_w W_t$.

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

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

where δ_b represents the fraction of body rockets that break up each period. The number of debris produced by the breakup of a large piece of debris is assumed to be equal to the number of debris produced by the breakup of rocket bodies $\sigma\delta_z Z_t$.

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

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

where γ is the amount of debris generated by a collision and destruction of satellites, and ω is the amount of debris produced per launch. In addition, explosions and breakups of derelict satellites and rocket bodies produces fragments in the quantity given by σ.

3. LAISSEZ-FAIRE COMPETITIVE DECENTRALIZED EQUILIBRIUM

First, we consider the case of a competitive decentralized economy without any mitigation policy. This is the baseline scenario (laissez-faire). In this setup, households and firms make decisions without taking into account the social cost of the negative externality of orbital debris, leading to damages that are not internalized. They simply adjust their decisions to the space environment. This is a realistic description that reflect the current situation in space, where no central authority exists, and spacefaring entities only take passive measures to protect themselves from debris collisions. Consequently, investment decisions in satellites incorporate the cost of collisions as an exogenously 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 firm's profit, all of them exogenous to the household. The household's maximization problem, taking into account the accumulation process for both capital and satellites, is as follows:

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

From the first order conditions for the household's maximization problem, equilibrium conditions 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 in the standard DICE model, endogenizing the saving rate has little impact. 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 moves toward equilibrium. Given the relatively constant nature of the savings rate, we can consider it a valid approximation. In this context, firms aim to maximize profits as optimizers. However, with the fixed saving rate, we solve a maximization problem for households to optimally allocate between Earth's capital and satellites. Therefore, the total investment, which is the sum of investment in Earth's capital and space 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 parameters. It takes into account the global economy and the characteristics of outer space as a shared global commons. A significant challenge in aggregating space-related variables is their dependence on altitude. Therefore, average values are used for the calibration of 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, both of 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 in 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 of our model. For comparison with NASA's catalogued 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 about 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 space debris is found 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 poses a low risk of catastrophic satellite damage, but it can still significantly impair critical systems and reduce operational lifespans. On the other hand, debris larger than 1 cm can be very dangerous due to the high velocity of collisions. Therefore, our model calibration takes into account the estimated quantity of debris larger than 1 cm using a proportional rule based on tracked debris.

4.1. Model parameterization

The production function is assumed to follow the Cobb-Douglas type, where labor 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 split of total investment between Earth and Space capital.

4.2. Calibration of economic parameters

The model is designed to be a global model that encompasses all human economic activities on Earth and in space. It takes into account these activities when calibrating economic parameters. 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 involves calibrating 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 use activity data for the calibration of the output-satellites elasticity parameter. Additionally, the model incorporates two technological growth processes: total factor productivity and investment-specific technological changes in satellites.

It is assumed that the sum of technological parameters for capital is $\alpha_1 + \alpha_2 = 0.35$, which implies a labor 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 (BEA, 2023), the Space industry contributed \$129.9 billion to the US economy in 2021 (0.6% of GDP) and provided 360,000 full- 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 (SIA, 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 labor, 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 concerning satellite equipment, we used data from BEA (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 and 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 to 8 years. Consider an average annual depreciation rate of 0.15 for satellites to simplify calculations for any orbit.

The parameters for the exogenous technological sources of growth have been selected following the literature and to produce an initial growth rate around 2%. The initial TFP growth rate is fixed 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 $\eta = 10$. Finally, the conversion parameter is calibrated by dividing the initial number of satellites (rounded to 8,500) between the value of satellites, measured in output units, resulting in 383,090.

4.3. Calibration of physical parameters

The model's physical parameters have been calibrated to match the evolution of orbital debris. Projections obtained using different models (Lewis, 2020) for debris proliferation (for example, 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 (Lewis, 2020). 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 velocity 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, and geomagnetic index. The most crucial factor is the altitude due to the atmospheric drag. The Australian Space Weather 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). We use the average of this figure as a reference, and therefore, the average lifetime is estimated at around 150 years. Assuming straight-line depreciation, this results in an annual decay rate of 0.0067.

	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
	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^{-10}	ESA/NASA
	χ	Fraction of abandoned satellites	0.35	ESA/NASA
	δ_d	Debris depreciation rate	0.0067	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 breakup	25	ESA/NASA
	γ	Number of fragments per collision	100	ESA/NASA

Table 1: Baseline calibration of the parameters of DISE

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 maneuver 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 $\theta = 1.25 \times 10^{-10}$.

When satellites run out of fuel and cannot be moved to graveyard orbits. This was quite a common occurrence during the first stages of space conquest. Abandoned satellites represent a risk, given their mass. 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 $\varphi = 0.40$. 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 number of fragments larger than 10 cm resulting from breakups (σ) is fixed to be 25.

The remaining parameters are the number of pieces of debris per launch (ω), and the number of fragments per collision (γ). The first parameter includes spent rockets and other parts discarded during satellite deployment into a target orbit. It is assumed that the number of debris larger than 10 cm per launch is 4. For the calibration of the second parameter, 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.[3] 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. Lewis et al. (2009) 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.

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 deorbiting policy starting in 2030, 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 an scenario with no debris to quantitatively measure the cost of orbital pollution.

5.1. Baseline: Laissez-faire

This represents the current situation, where no active action is taken to mitigate debris. The consideration of outer space as an international common resource and the difficulties for an international agreement to mitigate debris generation and reduce the stock of orbital debris give this scenario a high probability. In this baseline scenario households and firms take as given the stock of orbital debris, with no internalization of the social externality cost by any authority. Spacefaring 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. This is highly plausible since outer space is an international common resource and there are difficulties in reaching an international agreement to mitigate debris generation. This is the baseline scenario.

5.2. De-orbiting policy

One of the sources of orbital debris are derelict end-life satellites and upper stages of rocket bodies. These pieces of debris are of a large size and are tracked by surveillance systems. However, they pose an additional threat as they can breakup producing

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[3] 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.

thousands of fragments. Debris mitigation guidelines include recommendations for de-orbiting both non-operational satellites and rocket bodies. The international interest in the problem is reflected in the Inter-Agency Space Debris Coordination Committee (IADC) mitigation guidelines, which indicate the removal of space systems that interfere with the Low Earth Orbit (LEO) region no later than 25 years after the end of the mission. According to these non-binding guidelines, new spacecraft will need robust and reliable systems for de-orbiting.

In this scenario, we consider mandatory de-orbiting of end-life satellites and body rockets once the payloads have been inserted into orbit. IACD and other national space agencies have established a 25-year post-mission disposal rule to lower the threshold for disposing of dead satellites and rocket bodies by removing those in Low Earth Orbit (LEO) or boosting those in Geosynchronous Orbit (GEO, 36,000 kilometers about the Earth) to a higher 'graveyard' orbit. Rao et al. (2023) consider a disposal time of 5 years and compare the results with the 25-year de-orbit guideline. Here, we run the model by considering a 1 year post-mission disposal rule starting in 2030. Simulation of this scenario implies that $\chi = 0$, for the de-orbiting of end-life satellites, and $\varphi = 0$ for the de-orbiting of upper stage rocket bodies.

5.3. 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, and the payload deployment does not cause new debris. Debris-free launch systems have been developed in the past. For instance, NASA's 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 insert satellites into orbit like a Pez dispenser, avoiding debris generation, such as payload fairing parts. To simulate this scenario, we fix $\omega = 0$ and $\varphi = 0$.

5.4. Combination of de-orbiting and debris-free launch systems

This scenario considers simultaneously compulsory de-orbiting policy with the use of debris-free launch systems. For simulating this scenario, we set $\chi = \omega = \varphi = 0$.

5.5. No collision

In this scenario, it is assumed that all satellites and other types of spacecraft have maneuverability capabilities. Tracking systems can alert to possible collision, and satellite operators can perform collision-avoiding maneuvers. Note that tracking orbital debris and collision-avoiding maneuvers are costly. To simulate this scenario, the parameter θ is set to zero.

5.6. Clean space environment

Finally, we simulated a version of the model with no debris, representing a fictitious scenario with a clean space environment. This scenario is just used for quantify the cost of orbital debris by the comparison of output in this scenario with the other scenarios.

6. RESULTS

The model simulation is carried out annually for the next 200 years, starting from 2024, with the initial values of the variables corresponding to the year 2023.[4] The results can be compared with those obtained by Adilov et al. (2020), Nozawa et al. (2023), and Rao et al. (2023). Nozawa et al. (2023) show that if debris remediation strategies are not implemented, orbital debris will cause a negative impact of approximately 1.95% of global GDP over 200 years. A sensitivity analysis, using alternative values for the exogenous sources of growth and a range of values for some key parameters have been carried out, but main results remain. Trajectories of the variables show similar paths but the timing differs.

Figure 1 plots the number of satellites, number of launches, and the number of new satellites losses under the alternative scenarios. The number of satellites increases steadily over the whole period for the non-collision scenario. 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 loosing satellite assets is increasing over time, reducing the returns of investment in satellites. Three important findings are worth noting. First, de-orbiting dead satellites and debris-free launch systems scenarios produces similar results. This shows that the amount of derelict satellites and debris created by launch systems contributes similarly to the dynamics of orbital debris. Implementing a policy that requires end-of-life satellites to be de-orbited, as well as developing technology for launch vehicles that produce minimal debris, would contribute equally to reducing debris in the long run. Second, more than combining both scenarios is required to avoid a congested space environment that reduces the number of satellites in orbit. This means that combining a compulsory de-orbiting policy and using debris-free launch systems is not enough to mitigate the propagation of orbital debris to a point in which the optimal number of satellites in orbit reduces. Third, the gains concerning the laissez-faire (do nothing) scenario are already limited, except for the non-collision scenario where the number of satellites destroyed by collision is zero and no additional debris is generated from this source. The number of destroyed satellites follows similar paths.

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[4] MATLAB code is available upon request.

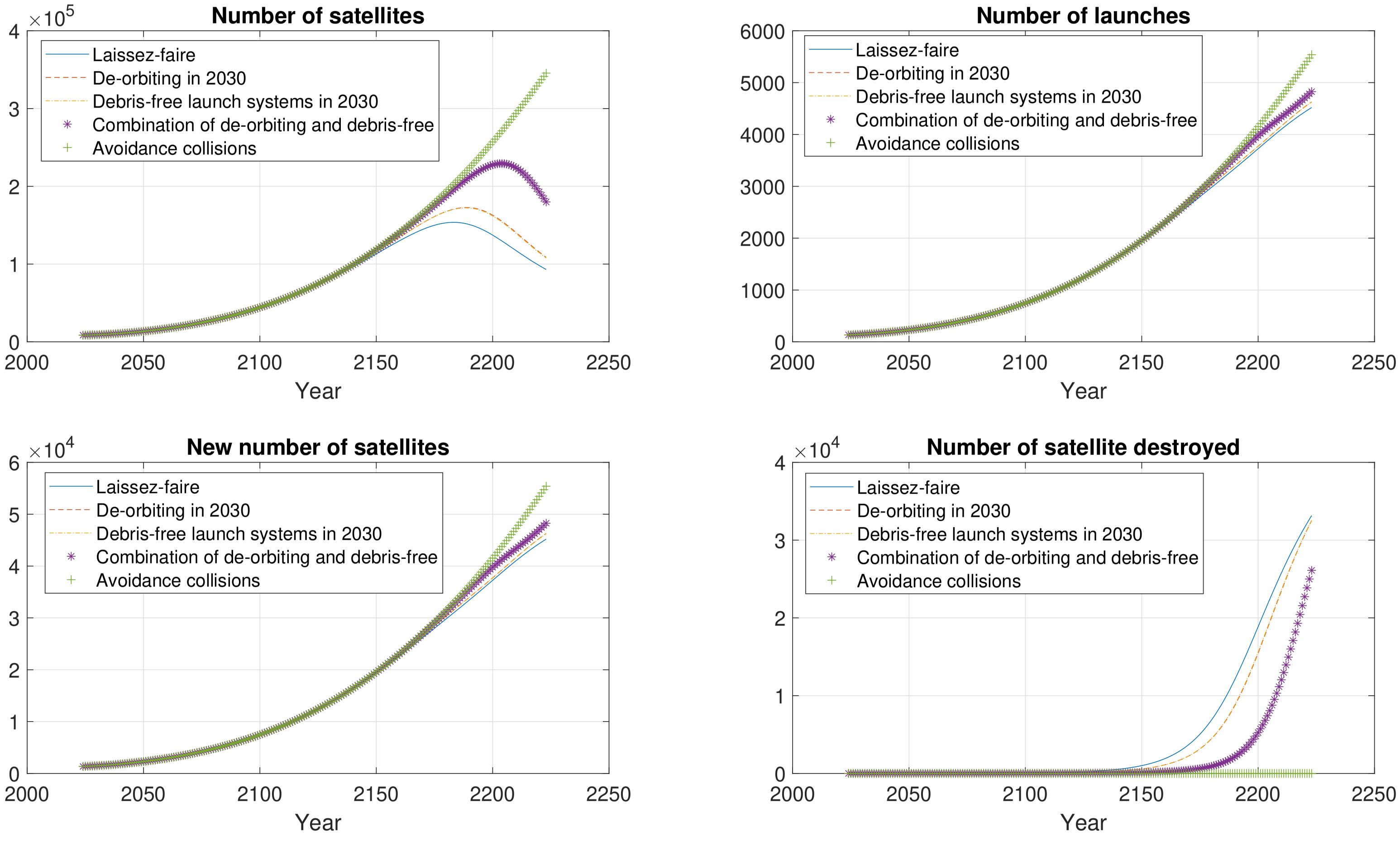

Figure 1: Tracking satellite stocks, launches, new satellites, and satellites destroyed by collisions

For the next 100 years, economic activity and space environment will be similar across all scenarios, with little differences among them. This is because the cost of orbital debris remains low, despite increasing economic and space activity. These results indicate that the problem posed by orbital debris is a long-term issue. However, the situation dramatically changes from the year 2150 onwards, where the accumulation of debris and satellites leads to a fast growth in the probability of collision, increasing the velocity in the generation of debris.

Figure 2 plots the number of objects in orbit, considering only fragments larger than 10 cm. The number of fragments increases exponentially in all scenarios except the non-collision scenario. This result is important, as the model simulation indicates that one of the future primary sources of debris production would be increased collisions between satellites and debris. During the first 100 years (up to the year 2125), the dynamics of orbital debris are fairly similar across the different scenarios. However, once the number of debris reaches a specific value, collisions are large enough to be the main driving force for debris growth. The combination of the de-orbiting policy and debris-free launch vehicle technology only delayed reaching a certain number of fragments a few years. The number of derelict satellites in orbit goes to zero for the de-orbiting policy. Similarly, in the case of rocket bodies in the debris-free launch systems scenario. However, the impact on the generation of fragments for these two scenarios and their combination is already limited in the long-run, just delaying a few years the stock of pollution in the space compared to the laissez-faire scenario.

In short, we find that exponential behavior in orbital debris is delayed but not stopped with mandatory de-orbiting policies and the use of debris-free launch systems. Only under the scenario of avoidance collisions the stock of debris remains under control during the simulation horizon. Better collision tracking systems and better technology for collision avoidance maneuvers seems to be the better option. Nevertheless, we are assuming that collisions only occur between debris and operational satellites, excluding the possibility of collisions between two pieces of debris.

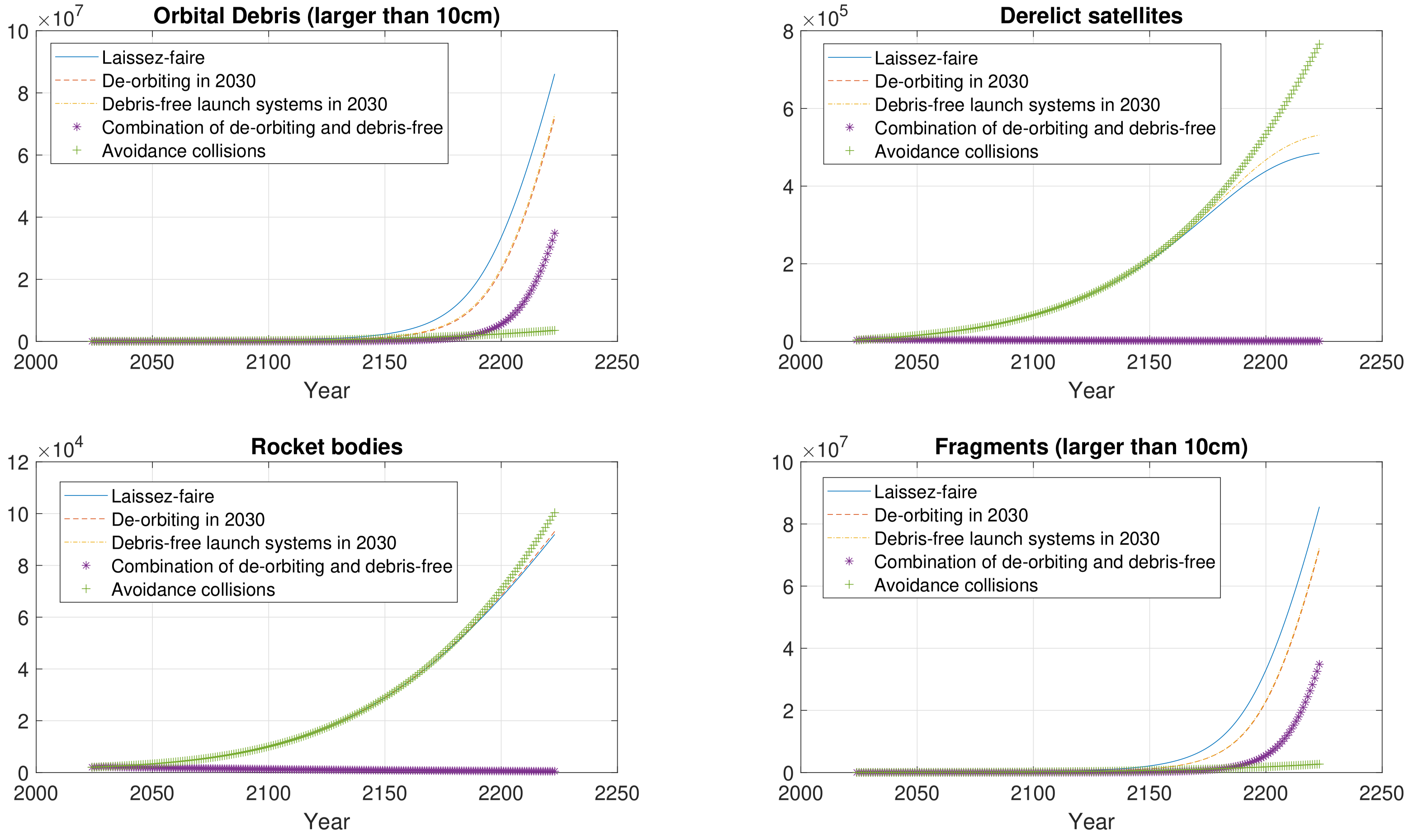

Figure 2: Number of objects in orbit: Derelict satellites, rocket bodies and fragments

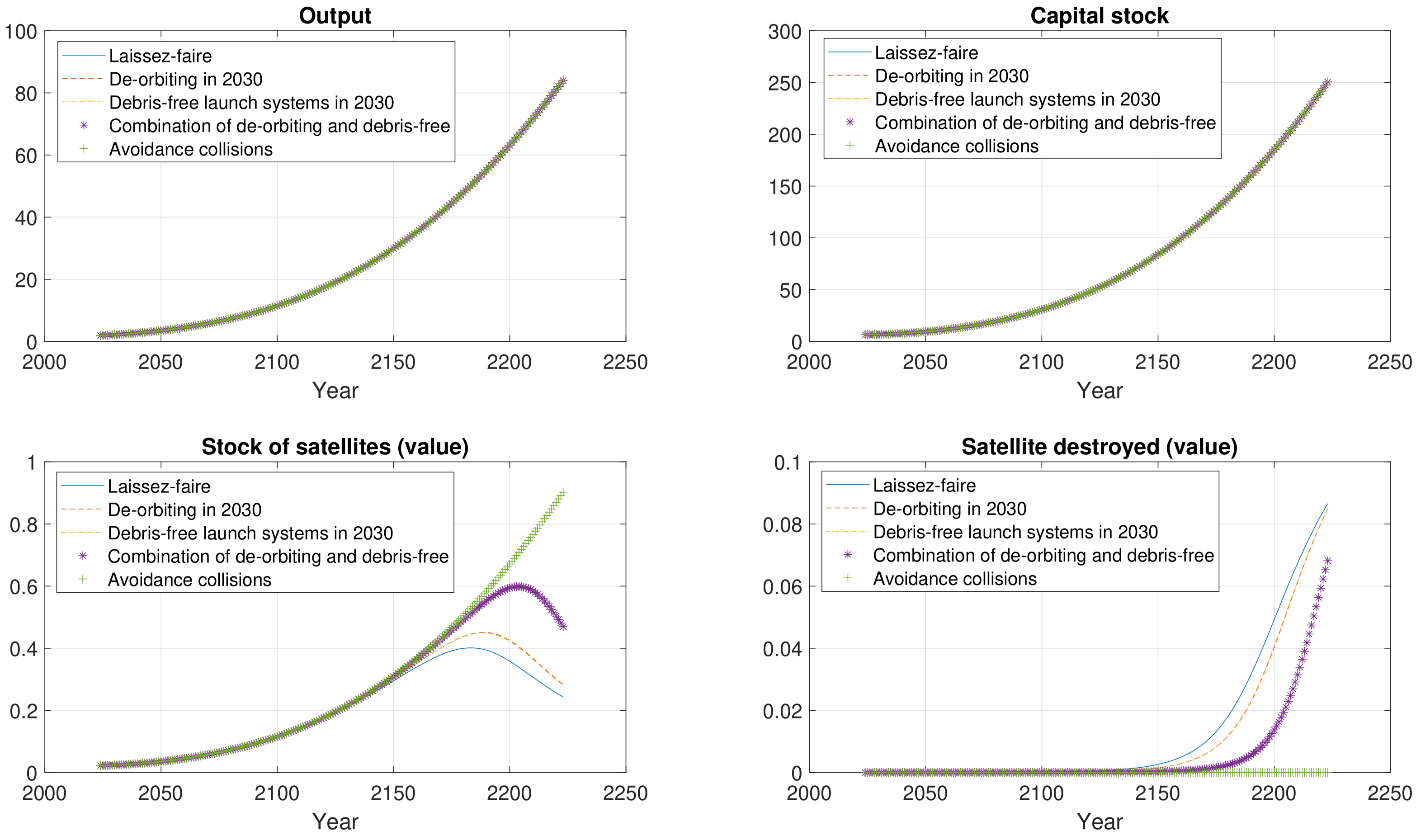

Figure 3: Output, capital stock, stock of satellites and value of satellites destroyed by collision

Figure 3 plots the trajectories for the main economic variables: output, value of Earth's capital, value of the stock of satellites in orbit, and the cost 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. In the baseline calibration of the model, the stock of space capital and the output-satellite elasticity. 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. This means the elasticity of output concerning the stock of satellites is a minimal number (0.0021) for all the simulation horizons. This provokes 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 be increasing in the future. 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, surprisingly, 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 essential 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.

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. 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 0.4% 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 scenarios de-orbiting and debris-free launches, and 0.2% in the combination of these two scenarios.

Similarly, Figure 5 calculates output losses concerning 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 increase to -1.11% in the next 200 years. Output cost is lower for the other scenarios, but also significant. For the de-orbiting

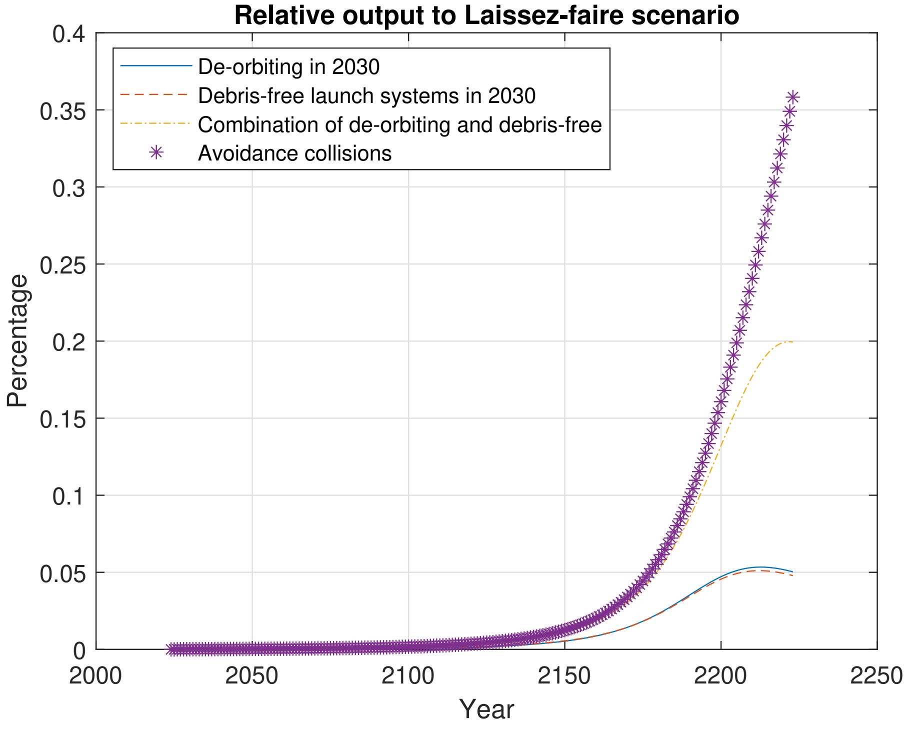

Figure 4: Output gains with respect to the Laissez-faire scenario

policy and the debris-free launch scenarios, the loss is around -1.08%, and 0.9% for the combination of both scenarios. For the non-collision scenario, output losses are around -0.75%.

Figure 6 plots the cost of collisions (the value of destroyed satellites over total output). This is a direct damages show an S-shape over the simulation horizon. De-orbiting policies and debris-free launch technology limit the damage concerning the laissez-faire scenario. However, at the end of the simulation horizon, damages are very similar for these scenarios, indicating that de-orbiting policies and debris-free launch technologies positively impact the short-run, reducing debris growth. Collisions also produce and additional cost generating debris. However, their effect is more limited in the long run as the primary source of debris production.

Finally, Figure 7 plots the collision probability for a satellite (θD_t). This would reflect how close the space environment is to the Kessler syndrome. Adilov et al. (2018) indicate that a probability of one collision 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 is 0.39 for the laissez-faire scenario, still far from the Kessler syndrome. However, as shown in previous figures, in any scenario with collisions, the economic Kessler syndrome (a point from which the number of satellites starts to decrease) is reached before the end of the simulation horizon.

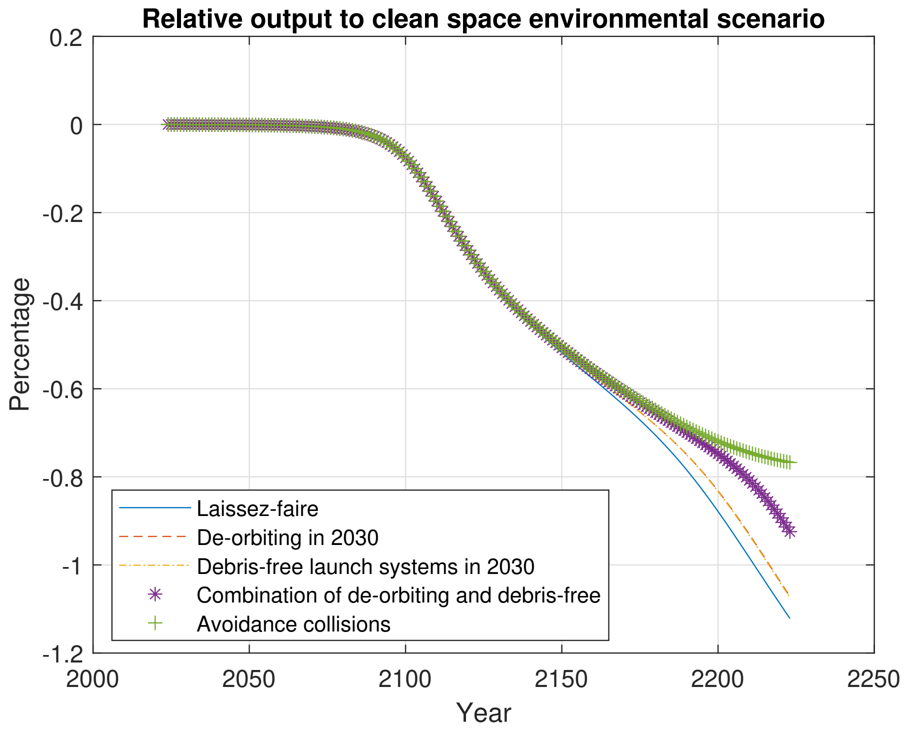

Figure 5: Output losses with respect to a space-clean environment

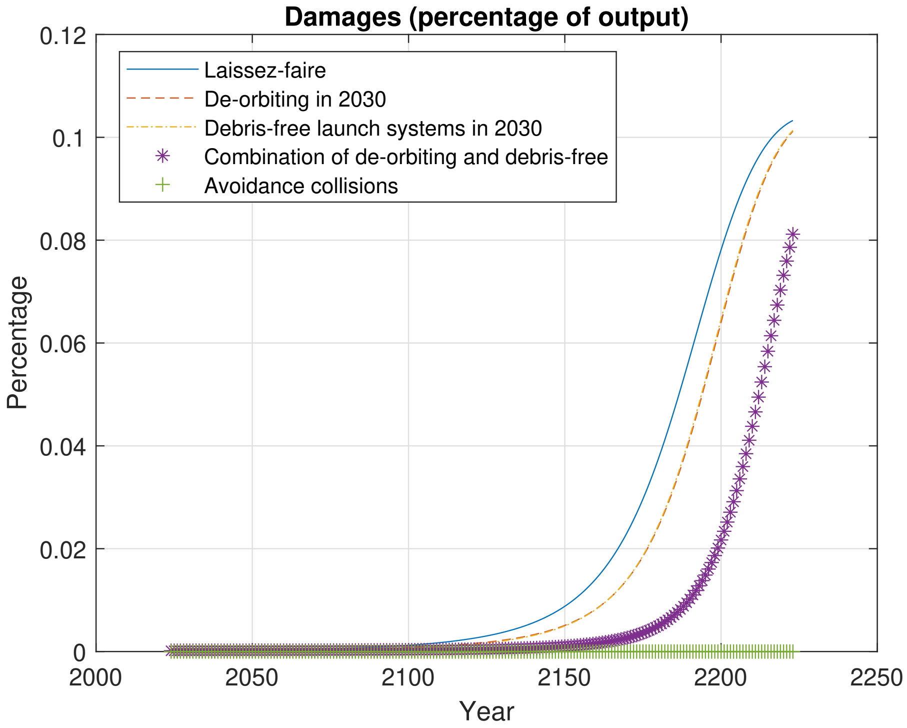

Figure 6: Output cost of collisions

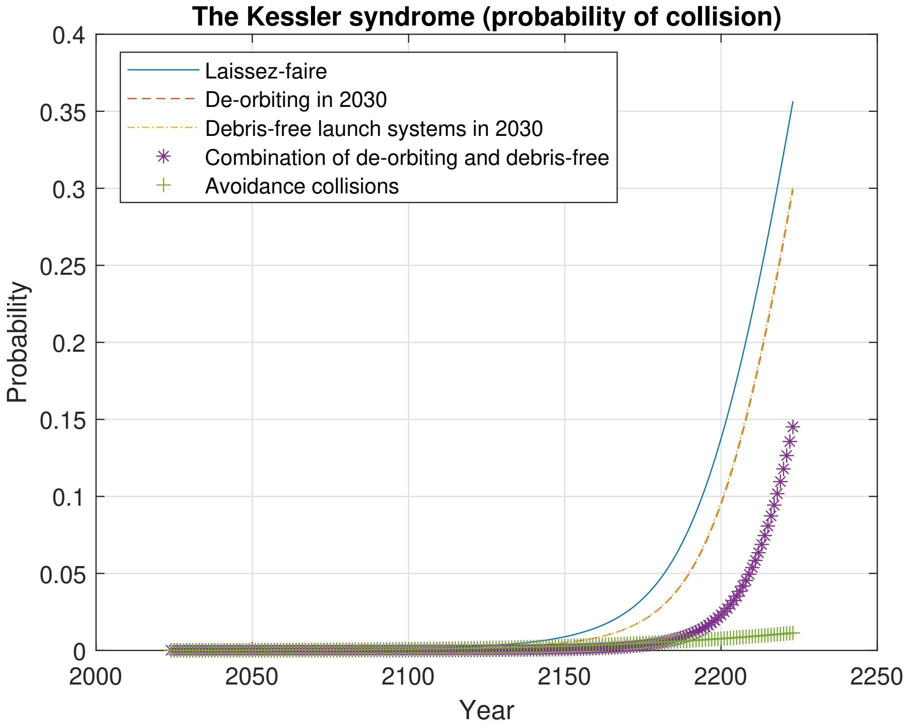

Figure 7: The Kessler syndrome: Probability of collision for satellite

7. CONCLUSIONS

This paper presents a type of integrated assessment model (IAM) for the space as a theoretical framework to study alternative policies to mitigate pollution problems in the space. The environmental negative externality arising in space consists of orbital debris, and damages come from collisions of orbital debris with operational satellites. Similarly to 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 are optimizers by maximizing profits and households make optimal decisions about the portfolio of capital assets subject to an exogenously given saving rate.

The model is simulated for a horizon period of 200 years, where the year 2023 is the base year, under alternative scenarios: laissez-faire, de-orbiting policy, debris-free launch systems, and no-collision. Additionally, the growth model is simulated for a space environment with no debris to obtain a measure of 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. Second, as time passes, the primary source of debris generation is collisions with operational satellites, resulting from the accumulation of satellites and orbital debris. Third, with the baseline calibration of the model, we find that the stock of satellites starts to decline before the probability of collision reaches one, ensuring that all satellites in orbit are destroyed by collision. This is consistent with the results of Adilov et al. (2018), who show that the “economic Kessler syndrome” takes place before the “physical Kessler syndrome”. Finally, the most important finding is that de-orbiting policies, elimination of breakups of rocket bodies and derelict satellites, and the development of debris-free launch systems all contribute to the short-run mitigation of orbital debris. However, they have a limited positive effect on the space environment in the long run, given the current level of orbital pollution, 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 the development of avoiding-collision technologies and the implementation of active debris removal (ADR) policies to clean the space environment.

Finally, the cost of damages is relatively small, given the modest elasticity of output concerning the stock of satellites. However, this hinders the increasing congestion in the space environment and the high number of collisions over time, reducing the satellite input. This small cost is a consequence of using Cobb-Douglas technology, where the elasticity of substitution between Earth’s capital and satellites is unitary. In practice, satellites produce some services that Earh’s capital cannot produce, limiting the substitution between Earth capital and Space capital.

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