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Optimal satellite shielding and orbital debris

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Abstract

Orbital debris, or space junk, is a major environmental externality that poses serious risks to human activity in outer space. The rapid increase in satellites and spacecraft from commercial, military, and scientific missions has intensified space pollution, leaving millions of debris fragments orbiting Earth at high velocities. This proliferation raises the likelihood of collisions and the destruction of operational spacecraft. This paper examines how spacecraft shielding affects both collision-related damage and debris generation. Shielding lowers the probability of satellite breakup during collisions, helping limit the creation of additional debris. It illustrates how spacefaring firms can mitigate the environmental costs of space activity through individual actions, even within a decentralized, profit-driven framework. Our analysis shows that when satellite operators invest in reducing collision risks and potential destruction, their behavior partially internalizes the externality, improving orbital sustainability. However, the optimal level of shielding in a decentralized economy remains below that achieved under a centralized framework, demonstrating that market mechanisms only partially address the negative externality.

Keywords Orbital debris · Satellites · Risk of collision · Shielding

Mathematics Subject Classification D62 · Q53 · L80

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1 Introduction

Since the launch of *Sputnik-1*, human activity in space has expanded rapidly, transforming the near-Earth environment into a vital component of modern civilization and a cornerstone of future exploration. Satellite technology and space-based infrastructure have revolutionized communication, navigation, Earth observation, and scientific research. Modern defense, national security, and military operations now depend heavily on satellite systems, while the militarization, and emerging weaponization, of outer space have advanced alongside the accelerating commercialization of the sector. Satellites underpin countless aspects of daily life: driving, watching television, navigating digital maps, flying, checking weather forecasts, and even withdrawing cash from ATMs all rely on satellite-enabled services. They are indispensable for transportation and logistics, telecommunications, agriculture, finance, natural resource management, and urban planning. Recent technological advances, particularly satellite miniaturization and declining launch costs, have fueled the rise of a new space economy, as private firms increasingly seek to exploit the vast commercial opportunities in Earth's orbit.

The rapid expansion of space activity has been accompanied by profound institutional and organizational transformations shaping the so-called New Space Economy. Recent research emphasizes the emergence of a complex space economy shaped by public–private partnerships, entrepreneurial ecosystems, and innovation-oriented policy frameworks (Lamine et al., 2021; Song et al., 2024). Space agencies such as NASA and ESA have played a central role in structuring knowledge development and technological trajectories, often in collaboration with private firms (Roy, 2025), while targeted entrepreneurial support programs have accelerated the growth of commercial satellite ventures and large constellations (Cavallo et al., 2025). These developments have significantly lowered entry barriers and increased the intensity of orbital activity, particularly in Low Earth Orbit, where commercial satellites and constellations are now densely concentrated. As emphasized by OECD (2022), the rapid commercialization of space has outpaced the development of effective international governance mechanisms, leading to coordination failures in the management of orbital resources. While this institutional evolution has enabled rapid innovation and commercialization, it has also amplified governance challenges in the orbital environment.

Yet this technological and economic progress has come at a cost: the progressive deterioration of the orbital environment, most notably through the growing accumulation of orbital debris, or "space junk" (Vittori et al., 2022). Orbital debris is a type of space pollution that could have dramatic consequences for commercial, military, and other human activities in outer space.[1] Human activities in space, including spacecraft launches, generate pollution in the form of orbital debris, a heterogeneous collection of objects ranging from upper-stage rocket bodies to tiny paint flakes. These fragments pose a significant risk to operational satellites and other spacecraft, as collisions with them can be catastrophic, potentially destroying the impacted satellite or

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[1] As defined by NASA, ”orbital debris is any human-made object in orbit that no longer serves a useful purpose, including spacecraft fragments and retired satellites”.

spacecraft (Liou & Johnson, 2006). Such collisions generate even more debris, further intensifying the problem. The volume of orbital debris has been steadily increasing since the beginning of space exploration. Although surveillance networks are able to track the largest fragments, smaller fragments must be estimated. The European Space Agency (ESA) estimates Earth's orbit contains approximately 130 million fragments larger than 1 mm, around 1.1 million fragments between 1 and 10 cm, and more than 30,000 fragments larger than 10 cm. Even tiny debris with minimal mass can cause severe damage due to the extreme velocities involved, typically around 10 kilometers per second. Moreover, space debris is self-propagating; collisions between debris create even more fragments in a cascading effect. This phenomenon, known as the ”Kessler Syndrome,” describes a scenario in which collisions continuously generate new debris, increasing the probability of further collisions (Kessler & Cour-Palais, 1978).

Orbital debris constitutes a type of endogenous, negative self-externality different from of terrestrial pollution. First, damages provoked by debris takes the form of the spacecraft (firms' capital assets) destruction which are also a further cause of debris emissions. Second, intact objects such as derelict satellites and upper abandoned stages rocket bodies can break due to residual fuel or battery explosion, producing large number of debris fragments and leading to an in-orbit, self-reinforcing process of debris accumulation. Moreover, the damage caused by orbital debris differs from that of Earth-based pollutants because as space pollution directly affects the capital assets of spacefaring nations and private firms (i.e., represents a negative self-externality). This unique characteristic of space pollution could lead to partial private internalization of the negative externality, even in a decentralized and unregulated environment.[2] In other words, any profit maximization strategy by spacefaring firms aimed at reducing the risk of losing their space assets creates a positive externality, by also reducing the emission of debris from in-orbit collisions, thus mitigating the negative externality of debris emission. To protect valuable space assets from of collision with orbital debris, spacefaring firms may adopt two main strategies: Spacecraft shielding and the implementation of collision avoidance systems. The first absorbs the impact energy to protect the spacecraft, while the second aims to prevent collisions altogether. Since collisions typically result in a spacecraft fragmenting into a cloud of debris, both strategies also help mitigate debris generation. Nevertheless, both strategies have limitations. Shielding is only effective against small debris fragments, while most debris is too small to be tracked to be avoided, limiting the effectiveness of collision avoidance systems under current technological capabilities.

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[2] In an unregulated environment, the social cost of negative externalities is not borne by the agents who generate them. This lack of cost internalization constitutes a market failure, as the private decision-maker does not account for the broader social consequences of their actions (Pigou, 1920). By "partial internalization", we mean a situation in which firms, acting according to profit-maximization, take measures to protect their space assets. These actions reduce the probability of breakups in the event of collisions with debris, thereby limiting the generation of additional debris. In this way, firms partially internalize the social cost of orbital debris without the need for regulatory intervention.

Several strategies have been proposed to mitigate the negative externality of orbital debris, including both active and passive policies.[3] However, no actively coordinated or mandatory international policy has been implemented to either reduce the generation of new orbital debris or remove existing debris from orbit. Current efforts remain limited to the adoption of standardized operational practices and satellite design guidelines aimed at minimizing debris creation. Kessler and Cour-Palais (1978) proposed several approaches to reduce orbital debris, including improved engineering designs to decrease the likelihood of satellite breakups due to structural failure or explosions, as well as measures to limit the accumulation of non-operational satellites in orbit. Macauley (2015) outlines three technological strategies for mitigating debris generation and collision risks: (i) Orbital maneuverability, allowing spacecraft to change orbit to avoid collisions; (ii) graveyarding capability, which involves relocating defunct spacecraft to either a high-altitude orbits (above 30,000 km) or a low-altitude orbits (below 500 km) for atmospheric reentry; and (iii) shielding, reinforcing satellites with stronger materials to reduce both the risk of destruction and the generation of additional debris in the event of a collision, although this method is only practical for small debris fragments. The most effective actions firms can take involve enhancing satellite quality by reducing the likelihood of collisions, minimizing damage in the event of an impact, and designing satellites to lower the risk of breakups and onboard explosions.

Seminal papers examining the economic consequences of orbital debris using different modeling approaches include (Adilov et al., 2015, 2018; Béal et al., 2020; Grzelka & Wagner, 2019; Guyot & Rouillon, 2021; Macauley, 2015; Rouillon, 2020; Vittori et al., 2022) among others.[4] Focusing on the strand of literature addressing protection against collisions, Macauley (2015) emphasized that firms can benefit from improving satellite quality. She examined how fee-based systems could incentivize investment in maneuvering capabilities and shielding, estimating costs under several tax mechanisms: harm-based taxes, graveyard taxes/rebates, and maneuver taxes/rebates. Adilov et al. (2015) compared market equilibrium outcomes with the social optimum and found that, because firms do not account for the negative debris externality, both the number of satellites and the number of launches exceed socially optimal levels. As the externality affects all firms, the result is underinvestment in debris mitigation technologies. Adilov et al. (2018) used a net present value approach to show that the threshold level of debris for economic viability is lower than the so-called "Kessler syndrome" threshold. Grzelka and Wagner (2019) developed a model exploring policies that stimulate ex-ante satellite quality improvements through intel-

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[3] Passive debris mitigation policies are generally framed as non-binding debris mitigation guidelines issued by national space agencies and coordinated through international bodies such as the United Nations Inter-Agency Space Debris Coordination Committee (IADC). Active debris mitigation efforts primarily focus on the development of new technologies for the removal of existing debris from orbit, a strategy commonly referred to as Active Debris Removal (ADR). However, ADR technologies are costly and face considerable practical and political challenges. Notably, there is currently no established cost-sharing framework among spacefaring entities, whether national agencies or private firms, which hinders coordinated implementation. Furthermore, and critically, the dual-use nature of these technologies raises significant security concerns, as they can be perceived as potential anti-satellite (ASAT) weapons.

[4] For a review of the literature, see Bongers et al. (2024)

lectual property protections and incentives for research and development, focusing on scenarios where firms enhance satellite quality and participate in debris retrieval. Rouillon (2020) found that firms launch too many satellites under perfect competition. Béal et al. (2020) compared the non-cooperative Nash equilibrium with a launch tax used to finance debris mitigation against the welfare outcome under a centralized tax. They found that a centralized tax results in higher optimal traffic and lower mitigation costs than the non-cooperative scenario. Guyot and Rouillon (2021) proposed a model in which satellite operators make design choices regarding durability, thereby influencing both performance and debris generation. Vittori et al. (2022) provided an empirical estimate of the economic cost of orbital debris in Low Earth Orbit (LEO).

To the best of our knowledge, only a few economic studies address satellite shielding, even though the topic is widely examined in space engineering (see Christiansen et al., 1999). Wiedemann et al. (2008) estimate the cost of satellite losses due to debris collisions while explicitly incorporating shielding costs. They conduct a cost-benefit analysis that compares the cost of shielding with the combined probability of debris impact penetration and the probability of satellite failure. Locke et al. (2024) provide a broader cost-benefit analysis of debris mitigation, tracking, and remediation, including estimates of shielding costs and collision-avoidance maneuver costs. They argue that spacecraft are equipped with shielding for two primary reasons: (1) protection, to reduce the probability that a mission ends due to a small-debris impact, and (2) mitigation, to increase the likelihood that the spacecraft will complete its post-mission disposal.

This paper investigates the economic and environmental implications of spacecraft shielding, represents an additional cost for the firms but also affects the law of motion of orbital debris. This involves reinforcing satellites with stronger materials to reduce both the risk of destruction and the creation of new debris from collisions, although this strategy is only practical for small debris. This paper contributes to the literature by developing a model that determines the optimal level of shielding, conditional on the probability of collision. The model extends the framework develop by Bongers and Torres (2023) by allowing spacefaring firms to choose both the optimal launch rate and the level of satellite protection. We show that shielding is an optimal profit-maximizing decision for individual firms to mitigate the risk of destruction of space capital assets. The option of shielding leads to an increase in the number of satellites and launches in steady state, as it reduces the velocity of accumulation of orbital debris, and reduces the number of satellites destroyed by collision. The model is solved for both centralized and decentralized scenarios.

We identify three key findings. First, the steady-state number of operational satellites and launches is lower than the initial levels due to the accumulation of orbital debris. Both launch activity and collisions contribute to debris generation, leading to a steady-state debris population approximately 100 times greater than the initial level in the benchmark scenario without shielding. Moreover, convergence to this steady state is relatively slow under current levels of space activity, as the orbital debris population stabilizes gradually over time. Second, we find that the optimal level of shielding is endogenously determined by the risk of collision, which itself depends on the amount of orbital debris. Firms' optimal shielding decisions mitigate debris accumulation, resulting in a higher number of operational satellites compared to the no-shielding case. This represents a specific example of partial private internalization of a negative externality: shielding generates a positive environmental externality that partially offsets the negative externality associated with orbital debris. Third, in the steady state, the central planner's solution involves a higher rate of shielding, which further reduces both the debris stock and the number of satellites lost to collisions, albeit at the cost of supporting a smaller satellite population compared to the decentralized equilibrium. This implies that, while private profit-maximizing behavior leads to some degree of internalization of the externality, it falls short of achieving the socially optimal level of debris mitigation.

The structure of the rest of the paper is as follows. Section 2 presents a simple economic model of satellites in which firms choose both the optimal number of launches and the level of satellite shielding. Section 3 calibrates the parameters of the model. Section 4 uses the calibrated model to simulate alternative scenarios. Section 5 discusses the implications of the results. Finally, Sect. 6 presents some concluding remarks.

2 A model for optimal shielding for satellites

We examine the market for orbital use, in which spacefaring agents determine both the optimal satellite launch rate and the level of protection against collisions. The model considers a representative firm.[5] The model can be solved under two alternative settings. The first corresponds to a centralized economy (a first-best world), in which a social planner fully internalizes the social cost of the externality and determines the optimal choices for firms (a fully macroeconomic perspective). The social planner takes the role of an international space regulator. The second corresponds to a decentralized economy, i.e., a market economy, in which individual firms make their optimal decisions without internalizing the social cost of the externality (a microeconomic perspective). The use of a representative firm model is justified by the structural nature of the orbital environment and by the global character of the externality. All spacefaring firms operate within a shared orbital domain where debris affects every participant through the same physical processes of collision risk and debris

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[5] The concept of a representative firm is commonly used in industrial economics and micro-founded macroeconomic models to simplify the analysis of aggregate economic behavior. It assumes that all firms are identical in terms of technology, production functions, and constraints, allowing the behavior of and industry or the aggregate economy to be represented by the actions of a single "representative" firm. In the context of orbital debris, the representative firm framework allows us to model how an individual firm's decisions regarding satellite design, shielding, and debris mitigation translate into macro-level outcomes for the overall orbital environment. The concept of a "representative firm" originates in Marshall (1890), who introduced it as an analytical device to model industry behavior through a typical firm. This idea was later formalized in modern investment theory through Tobin's Q model (Tobin, 1969), with Hayashi (1982) establishing the conditions under which the representative-firm framework is internally consistent. A closely related construct is widely used in macroeconomic models under assumptions of perfect competition and constant returns to scale, as in Kydland and Prescott (1982). In the context of environmental and resource economics, representative-firm models are commonly used to study externalities and policy design when emissions or damages depend on aggregate activity rather than on individual firm identity (e.g., Nordhaus, 1993).

propagation. Since the probability of collision depends on aggregate orbital congestion rather than on individual firm identities, the representative-firm framework provides an analytically coherent way to capture the average behavior of the industry as a whole. This abstraction allows us to focus on the fundamental interaction between private incentives, shielding decisions, and the evolution of the debris stock, without introducing firm-specific heterogeneity that would not qualitatively alter the system's aggregate dynamics.[6]

Due to the global commons nature of orbital space, the negative externality from space pollution is not fully internalized in a decentralized market economy. Nonetheless, individual agents, such as commercial space firms, may make profit-maximizing decisions in response to collision risk, thereby influencing the debris generation process. In this setting, firms make decisions without accounting for the broader consequences imposed on other market participants. However, self-interested behavior may still produce positive spillovers for the overall system. This occurs because orbital debris directly threatens a firm's capital stock, that is, operational satellites, prompting strategic responses aimed at preserving those assets. This mechanism contrasts with many Earth-based externalities, where pollution affects social welfare or overall productivity but does not directly impinge on the capital assets of individual firms. In the case of space, by contrast, the externality has a direct and measurable impact on a firm's revenue-generating capacity through the destruction of its satellites. While this does not constitute a socially optimal internalization of the externality, it reflects a unique situation in which firms' private incentives are partially aligned with broader environmental outcomes due to the direct threat to their capital.

2.1 The model

We consider a representative firm launching and operating satellites. The representative firm faces two types of costs: launch costs and shielding costs. Launch costs include all expenses associated with inserting a satellite into the target orbit, including the cost of the satellite, but excluding any costs associated with the shield, which are included in the shielding cost. Shielding technology reduces the risk of destruction in case of collision and is modeled as an additional production cost and as a factor mitigating both the destruction of satellites and the number of debris generated by the destruction of satellites. This type of protection is known as the "Whipple shield".[7]

Shielding cost not only include the cost of the Whipple shield but also all costs associated with the increase in the volume and weight of the satellite. Firms choose

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[6] Moreover, in the early stages of the commercial space economy, firms face relatively homogeneous technological and physical constraints, especially within given orbital shells (e.g., low Earth orbit). The representative firm can therefore be interpreted as the average operator in a competitive sector exposed to identical debris hazards and making decisions under similar cost and risk structures. While future research could incorporate firm heterogeneity and strategic interaction, the representative-firm approach is sufficient to characterize the equilibrium relationship between individual shielding decisions and collective orbital sustainability, and to highlight the partial internalization mechanism that emerges endogenously from firms' shared exposure to a global externality.

[7] Whipple shield (proposed by Whipple (1947)) consists of several layers of materials around critical parts of spacecraft designed to absorb the energy of hypervelocity impact of micrometeorids or orbital debris. This protection is effective for debris smaller than 2 cm (Locke et al., 2024).

the optimal launch rate and the level of shielding for launched satellites. We assume the following technology function for satellite services:

$$Y_t = A_t S_t^{\alpha} \tag{1}$$

where Y_t denotes satellites services, and S_t is the number of operational satellites in orbit. The parameter α $(0 < \alpha < 1)$ represents the elasticity of satellite services with respect to the number of satellites, which is assumed to be lower than one, indicating the existence of decreasing returns to scale given a demand for satellite services. A_t is a measure of productivity, representing technological change in the production of satellite services, which is assumed to be exogenous.[8]

The majority of debris is too small to be tracked and avoided. The only protection against this small debris is shielding. Spacecraft are shielded by adding layers of additional mass that absorb the energy of the impact and prevent the debris from penetrating the spacecraft. The added mass contributes to increased launch and manufacturing costs. Locke et al. (2024) parameterized shielding by the amount of added mass required to shield critical areas from debris penetration as a function of debris size and estimated the amount of shielding potentially needed for the spacecraft to reach a given level of protection. Typically, the mass of the shielding increases exponentially with the level of protection.

Following Locke et al. (2024), we assume the existence of an additional cost of operating satellites from shielding, given by the function $h(h_t)$, where h_t $(0 < h_t < 1)$ represents the endogenous decision by the firm regarding satellite's shield hardness, from no protection again impacts ($h_t = 0$) to indestructible ($h_t = 1$). It is assumed that $h'(h_t) > 0$, and $h''(h_t) > 0$, reflecting exponential costs of augmenting shielding. It is assumed that shielding cost adopts the following specification,

$$h\left(h_t\right) = \left(\exp\left(\phi h_t\right) - 1\right) \tag{2}$$

where the parameter $\phi > 0$ reflects the cost of shielding.

Infinity-lived representative firm operating in the outer space maximizes the sum of the discount profits (the present value of future receipts, V_0), defined as Π_t,

$$\max_{S_t, h_t} V_0 = E_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \Pi_t \tag{3}$$

where E_t is the expectation operator, $1/(1+r)$ is the discount factor, and where r is the interest rate which is assumed to be constant. Profits are defined as,

$$\Pi_t = Y_t - \left[c + \exp\left(\phi h_t\right) - 1\right] L_t \tag{4}$$

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[8] Within this theoretical framework, S_t can be interpreted either as the capital stock of the representative firm or, equivalently, as the aggregate number of satellites in orbit. Similarly, Y_t represents the services provided by the representative firm, or, at the market level, the total services produced. In the calibration of the model, we interpret these variables as the whole market. Since the price of satellite services has been normalized to one, Y_t can also be interpreted directly as revenues.

where Y_t represents income from satellite services, where the price of satellite services has been normalized to one, L_t is the number of satellites launched, and c represents the cost per satellite launch.[9] For simplicity, we assume that c is exogenously given and that space operating firms have perfect-foresight. The parameter $\phi > 0$, reflects the cost of achieving a level of protection against destruction in case of collision of shielding.

The stock of operational satellites in orbit at period $t + 1$ follows the following process,

$$S_{t+1} = (1 - \delta_s) S_t + L_t - X_t \tag{5}$$

where $0 < \delta_s < 1$ is the depreciation rate of satellites, and X_t is the number of destroyed satellites due to collisions with debris every period. We follow Farinella and Cordelli (1991) and Rossi et al. (1997), and we assume that the collision rate is proportional to the product of debris and operational satellites. We also assume that, in case of collision, the satellite is destroyed and that the collision creates a number of new debris. We assume that the destruction function is now given by,

$$X_t = (1 - h_t) \theta D_t S_t \tag{6}$$

where the term $\theta D_t S_t$ results in the number of satellites destroyed every period by collisions with debris. The proportional parameter $\theta > 0$ represents the probability of collision between two objects in orbit. It is assumed that the probability of collision of a satellite is proportional to the quantity of debris, θD_t. The probability of destruction of a satellite from a hit, given a probability of collision, is reduced by the term $1 - h_t$. This means that, in case of a collision, the quantity of satellites destroyed decreases, as well as the new debris generated by the collision. Notice that the negative externality affecting final output is modeled in a different way from standard environmental externality on Earth, where it is assumed that the stock of pollution negatively affects to output (productivity) or households' utility in a direct way. Here, the negative externality directly impacts the stock of capital assets (satellites), and investment is represented by launches.

The debris follows an accumulation process depending on how new debris is produced each period. In modeling the debris accumulation process, we consider two main sources: destroyed satellites and launches. Unlike any other source of pollution, the dynamics of space debris includes a self-propagating mechanism, where pollution generates additional pollution. That is, debris not only collide with satellites, but also with other pieces of debris, producing additional debris. The law of motion of debris is given by,

$$D_{t+1} = (1 - \delta_d) D_t + \omega L_t + \gamma X_t \tag{7}$$

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[9] The number of satellites launched is not equal to the number of rocket launches, as a rocket can carry more than one satellite.

where $\omega > 0$ is the number of debris generated per launch, $\gamma > 0$ is the number of new debris generated by the destruction of a satellite. As above, we assume that the probability of collision is proportional to the quantity of debris. It is assumed that debris generated per launch include explosions and fragmentations by upper-stage rockets. The parameter δ_d $(0 < \delta_d < 1)$ represents the natural decay rate of debris. This decay rate of debris mainly depends on atmospheric drag and solar conditions, and therefore is a function of the altitude of the orbit. The higher the altitude (with respect to the Earth) of the orbit, the lower the decay rate (NASA, 2018). Additionally, non-functional satellites (end-of-life satellites) represents also a type of debris if not removed from orbit. To simplify, we assume that all satellited are moved to a graveyard orbit at the end of their operational lives. Finally, collisions among debris and generation of debris by intentional destruction (anti-satellite military tests) are also neglected.

Maximization problem for the firm can be defined as:

$$\max_{S_t, h_t} V_0 = E_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[A_t S_t^{\alpha} - \left(c + \exp\left(\phi h_t\right) - 1\right) L_t\right] \tag{8}$$

subject to the corresponding constraints.

2.2 Decentralized economy

First, we study the case in which the representative firm chooses the optimal level of shielding to maximize profits. In this environment, the objective of the firm is to defend its own satellites and minimize damage from collisions. In a decentralized economy, the representative firm maximizes (8) subject to (5) and (6) by choosing the optimal number of satellites, launches, and the level of shielding. The Lagrangian auxiliary function can be defined as,

$$\begin{aligned}\max_{S_t, h_t} V_0 =& E_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[A_t S_t^{\alpha} - \left(c + \exp\left(\phi h_t\right) - 1\right) L_t\right] \\ & - \sum_{t=0}^{\infty} \lambda_t \left[S_{t+1} - \left(1 - \delta_s\right) S_t - L_t + X_t\right] \\ & - \sum_{t=0}^{\infty} \mu_t \left[X_t - \left(1 - h_t\right) \theta D_t S_t\right]\end{aligned} \tag{9}$$

The first-order conditions for optimality for $t = 0, 1, 2, ...\infty$, are,

$$S_{t+1}: \quad \left(\frac{1}{1+r}\right)^{t+1} \alpha A_{t+1} S_{t+1}^{\alpha-1} - \lambda_t + \lambda_{t+1}\left(1 - \delta_s\right) + \mu_{t+1}\left(1 - h_{t+1}\right)\theta D_{t+1} = 0 \tag{10}$$

$$L_t: \quad -\left(\frac{1}{1+r}\right)^t (c + \exp(\phi h_t) - 1) + \lambda_t = 0 \tag{11}$$

$$X_t: \quad -\lambda_t - \mu_t = 0 \tag{12}$$

$$h_t: \quad -\left(\frac{1}{1+r}\right)^t \phi \exp(\phi h_t) L_t + \mu_t \theta D_t S_t = 0 \tag{13}$$

where the Lagrangian's multiplier λ_t represents the shadow price of a satellite, and μ_t, represents the shadow price of a destroyed satellite, and it is equal to the (negative) shadow marginal benefit of launching a satellite, λ_t, as defined previously. From the optimality conditions, we find the optimal quantity of satellites and the optimal level of protection. Both variables are functions of the amount of debris. Notice that from the first order condition for the number of satellites destroyed by collision $\lambda_t = -\mu_t$. The optimal shielding decision is given by,

$$\phi \exp(\phi h_t) L_t = [c + (\exp(\phi h_t) - 1)]\, \theta D_t S_t \tag{14}$$

where the optimal level of shielding is positively related to the probability of collision and negatively related to the number of satellites in orbit. In the presence of orbital debris, firms choose to invest in shielding by weighing the cost of protection against the expected revenue gains from preserving satellites that would otherwise be lost in collisions. Importantly, this individual optimization behavior also generates a positive externality by reducing the amount of new debris produced during collisions. In the model, this effect is captured through a lower number of satellite destructions, which constitute a significant source of debris generation.

Solving for the optimal quantity of satellites, we obtain that,

$$S_{t+1} = \left(\frac{(1+r_t)[c + \exp(\phi h_t) - 1] - [c + \exp(\phi h_{t+1}) - 1][1 - \delta_s - (1 - h_{t+1})\theta D_{t+1}]}{\alpha A_{t+1}}\right)^{\frac{1}{\alpha - 1}} \tag{15}$$

Given the impact of satellite design characteristics, specifically shielding, on debris generation, the steady-state stock of orbital debris will differ, and consequently, so will the number of operational satellites, the number of satellites destroyed by collisions, and the launch rate. In this scenario, the equilibrium number of destroyed satellites is lower due to the protective effect of shielding. A key positive outcome is that the equilibrium stock of debris is also reduced as a consequence of shielding. This result is driven by two main factors. First, the reduced number of satellite losses leads to a decline in debris generation from collisions, which is one of the primary sources of new debris. Second, fewer destroyed satellites imply a reduced need for replacement launches, further decreasing debris accumulation, as launches also contribute to debris generation. Additionally, shielding lowers the number of debris fragments produced per collision, which is equivalent to a reduction in the parameter γ. Thus, shielding not only decreases the probability of satellite destruction in the event of a collision but also limits the quantity of debris generated when such collisions occur.

2.3 Centralized economy

Next, we consider a centralized environment, where we determine the socially optimal level of shielding by fully internalizing the negative externality of debris. In this context, the central planner maximizes (8), subject to (5), (6) and (7). The Lagrangian auxiliary function can be defined as,

$$\begin{aligned}\max_{S_t,h_t} V_0 =& E_t \sum_{t=0}^{\infty} \left(\frac{1}{1+r}\right)^t \left[A_t S_t^{\alpha} - \left(c + \exp\left(\phi h_t\right) - 1\right) L_t\right] \\ &- \sum_{t=0}^{\infty} \lambda_t \left[S_{t+1} - (1-\delta_s) S_t - L_t + X_t\right] \\ &- \sum_{t=0}^{\infty} \mu_t \left[X_t - (1-h_t)\theta D_t S_t\right] \\ &- \sum_{t=0}^{\infty} \zeta_t \left[D_{t+1} - (1-\delta_d) D_t - \omega L_t - \gamma X_t\right]\end{aligned} \tag{16}$$

First-order conditions for $t = 0, 1, 2, ...\infty$, are,

$$S_{t+1}: \quad \left(\frac{1}{1+r}\right)^{t+1} \alpha A_{t+1} S_{t+1}^{\alpha-1} - \lambda_t + \lambda_{t+1}(1-\delta_s) + \mu_{t+1}(1-h_{t+1})\theta D_{t+1} = 0 \tag{17}$$

$$L_t: \quad -\left(\frac{1}{1+r}\right)^t (c + \exp(\phi h_t) - 1) + \lambda_t + \omega \zeta_t = 0 \tag{18}$$

$$X_t: \quad \gamma \zeta_t - \lambda_t - \mu_t = 0 \tag{19}$$

$$h_t: \quad -\left(\frac{1}{1+r}\right)^t \phi \exp(\phi h_t) L_t + \mu_t \theta D_t S_t = 0 \tag{20}$$

$$D_{t+1}: \quad \mu_{t+1}\left(1-h_{t+1}\right)\theta S_{t+1} - \zeta_t + \zeta_{t+1}\left(1-\delta_d\right) = 0 \tag{21}$$

where the Lagrange multiplier, ζ_t, represents the shadow cost of debris. Lagrange multipliers are the following,

$$\mu_t = -\frac{\left(\frac{1}{1+t}\right)^t \phi \exp(\phi h_t) L_t}{\theta D_t S_t} \tag{22}$$

$$\lambda_t = \frac{\gamma}{\gamma+\omega}\left(\frac{1}{1+r}\right)^t \left[(c + \exp(\phi h_t) - 1)\right] + \frac{\omega}{\gamma+\omega}\left(\frac{1}{1+r}\right)^t \left[\frac{\phi \exp(\phi h_t) L_t}{\theta D_t S_t}\right] \tag{23}$$

$$\zeta_t = \left(\frac{1}{1+r}\right)^t \frac{1}{\gamma+\omega}\left[(c+\exp(\phi h_t)-1) - \frac{\phi\exp(\phi h_t)L_t}{\theta D_t S_t}\right] \tag{24}$$

Substituting the Lagrangian multipliers into the first and last FOCs, we get the following two equilibrium conditions for the optimal number of satellites,

$$\begin{aligned}\alpha A_{t+1}S_{t+1}^{\alpha-1} = {} & (1+r)\left(\frac{\gamma}{\gamma+\omega}(c+\exp(\phi h_t)-1) + \frac{\omega}{\gamma+\omega}\frac{\phi\exp(\phi h_t)L_t}{\theta D_t S_t}\right) \\ & - \left[\frac{\gamma}{\gamma+\omega}(c+\exp(\phi h_{t+1})-1) + \frac{\omega}{\gamma+\omega}\frac{\phi\exp(\phi h_{t+1})L_{t+1}}{\theta D_{t+1}S_{t+1}}\right](1-\delta_s) \\ & + \frac{\phi\exp(\phi h_{t+1})L_{t+1}}{S_{t+1}}(1-h_{t+1})\end{aligned} \tag{25}$$

and for the optimal shielding level,

$$\begin{aligned}\frac{\phi\exp(\phi h_{t+1})L_{t+1}(1-h_{t+1})}{D_{t+1}} = {} & \frac{1}{\gamma+\omega}(1+r)\left(c+\exp(\phi h_t)-1+\frac{\phi\exp(\phi h_t)L_t}{\theta D_t S_t}\right) \\ & - \frac{1}{\gamma+\omega}\left(c+\exp(\phi h_{t+1})-1+\frac{\phi\exp(\phi h_{t+1})L_{t+1}}{\theta D_{t+1}S_{t+1}}\right)(1-\delta_d)\end{aligned} \tag{26}$$

3 Calibration

The model includes both economic and physical parameters. For the calibration of physical parameters related to the orbital debris dynamics and human activity in space we use information from the NASA and the European Space Agency (ESA). The natural debris decay rate (δ_d) is calibrated by assuming an average value that takes into account the distribution of objects in orbit. The decay rate of debris depends on several factors, including altitude, mass, area, solar radioflux, and geomagnetic index. The most important factor is altitude due to atmospheric drag. The Australian Space Weather Agency (1999) estimated that the lifetime of space objects varies as follows: 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, the distribution of debris as a function of altitude is not homogeneous. The spatial density of debris indicates that it is concentrated in the range 700–900 km (NASA, 2020). To calibrate this parameter we use data from the NASA's breakups database in Anz-Meador et al. (2022). We use a value of 1% per year which roughly corresponds to an average altitude of 750 km.

The risk of collision (θ) is taken from the literature. Farinella and Cordelli (1991) estimated a value of $\theta = 3 \times 10^{-10}$, for an estimated debris quantity of 50,000. This means that the number of satellites destroyed per year is 0.2, given a collision probability $(\theta \times 50,000)$ of 1.5×10^{-5}. The total probability of collision for objects larger than 10 cm is approximately 0.1 for orbits between 800-900 km, 0.05 for orbits between 900 and 1000 km, and 0.025 for those between 600 and 700 km. Lafleur (2011) estimates a value of $\theta = 6.895 \times 10^{-10}$. Following Farinella Cordelli (1991) we take an estimated total probability of collision of 0.2 (i.e., one fatal collision every

5 years) as the reference, given the number of incidents observed in recent years (four collisions occurred between 1991 and 2009), resulting in a collision probability of $\theta \times D = 6.6 \times 10^{-5}$. Given a total number of potentially hazardous debris pieces of 1,036,500, this results in a collision risk parameter value of $\theta = 1.25 \times 10^{-10}$.

The number of pieces of debris per launch (ω) determines the primary source of debris generation. In our simplified debris emission model, this parameter includes not only expended rocket stages and other components discarded in the process of inserting a satellite into its target orbit but also debris generated by launch vehicles explosions. Johnson et al. (2001) use the NASA Breakup model EVOLVE 4.0 to estimate the number of new fragments from an explosion of 238 larger than 10 cm, and 9,509 fragments larger than 1 cm. Lewis et al. (2009) estimated that explosions generate 50 fragments larger than 10 cm and that, on average, 2.75 intact objects are added to the orbital environment per launch. Farinella and Cordelli (1991) estimated this parameter by assuming an average of two unintentional explosions per year, each generating several thousand fragments with a mass greater than 1 g, resulting in 70 new pieces of debris larger than 1 cm. We adopt this value and set $\omega = 70$. Finally, the number of pieces of debris per collision (γ), is taken from Farinella and Cordelli (1991) and Lafleur (2011), who estimate that each collision produces 10,000 fragments larger than 1 cm (see Table 1).

For economic parameters, we use standard values from the literature. Interest rate is fixed at 4% per year ($r = 0.04$), whereas the productivity parameter is normalized to one, $A = 1$. The technological parameter for the satellite services production function, α, is fixed at 0.85. We calibrate the launching cost internally to match observed values for the number of satellites using expression (17), resulting in $c = 1.10698$, for a quantity of 11,000 satellites and an amount of 1,100,000 debris fragments. For the calibration of the depreciation rate of satellites, we use data from NASA. 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. For LEO satellites the life-span varies from

Table 1 Calibration of the parameters of the model

	Parameter	Definition	Value
Physical	δ_s	Satellite depreciation rate	0.15
	δ_d	Debris decay rate	0.01
	θ	Risk of collision	1.25×10^{-10}
	γ	Number of debris per collision	10,000
	ω	Number of debris per launch	70
Economic	c	Launch cost	1.10698
	ϕ	Shielding cost parameter	0.066
	A	Productivity parameter	1.00
	α	Elasticity of satellite services	0.85
	r	Interest rate	0.04

3 to 8 years. To simplify calculations for any orbit, we consider an average annual depreciation rate of 0.15 for satellites. Bongers and Torres (2023) assume an average lifetime of 8 years, so the annual depreciation rate for satellites is fixed at 0.1733, whereas (Nozawa et al., 2023) use a depreciation rate for satellites of 0.216.

Finally, the shielding cost function is calibrated using estimates from Locke et al. (2024). These authors estimate the shielding cost for satellites as a function of the size of the spacecraft and the level of protection against debris of a particular size. Locke et al. (2024) estimate that stopping a 1 cm projectile requires shielding weighing between 10 and 20 kilograms per square meter, based on estimates by NASA (2009). Satellite masses range from 0.13 to 1.3 kilograms for microsatellites and from 10 to 100 kilograms for large satellites. We select an average mass of 20 kilograms for our calibration. Locke et al. (2024) estimate that shielding increases launch cost by $5000 per kilogram. For protection against the smallest size of dangerous debris, 1 cm, this means an increase in the launch cost of $50,000 per satellite. They also consider a shielding installation cost ranging between $0 and $100,000 per kilogram. We consider an average cost of $10,000 per kilogram, which implies a cost of $100,000 for protecting against 1 cm debris. From those estimates, we obtain that shielding increases the cost by 0.6%, which results in $\phi = 0.066$.

4 Quantitative simulations

In this section, we use the calibrated model to investigate the optimal level of shielding and its impact on the space environment. First, we study the transition dynamics of key variables to their steady state, given the baseline calibration of the model to the current space environment. Second, we focus on the study of the steady state of the model under three alternative scenarios: No-shielding, firms individually choosing the optimal shielding rate to maximize profits, and a central planner who fully internalizes the negative externality using the shielding level as an environmental mitigation instrument. We also investigate how reducing the shielding cost parameter affects the steady state solutions for a decentralized economy and a central planner economy. The baseline calibration is designed to match the current situation in the space. We use baseline values of 11,000 satellites and a debris population larger than 1 cm of 1,100,000, according to ESA's estimates. It is worth noting that a steady state only exists if no ”Kessler syndrome” scenario of cascade collisions appears, which would imply that the population of debris is continually increasing. We find that, under the baseline calibration, a steady state exists, as the Kessler Syndrome can be avoided by reducing the number of satellites and launches, and by increasing the level of shielding, such that debris emissions are balanced by their natural decay rate.

Figure 1 plots the transition dynamics from the initial situation to the steady state for the number of satellites, the population of debris, the number of launches, and the satellites destroyed by collisions for the three scenarios. Spacefaring firms activity in space leads to a rise in the amount of orbital debris over time. This rise is not only the consequence of the number of launches, but also of the increasing probability of collisions as the number of objects in space grows. These collisions increase the number of satellites destroyed and generate further debris, even though the number of

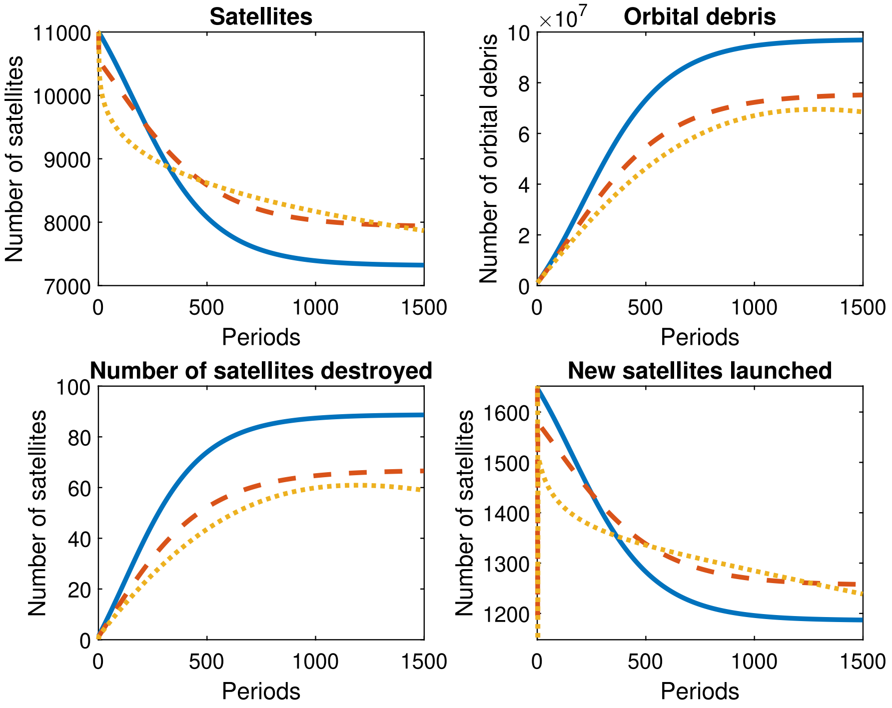

Fig. 1 Trajectories from initial values to the steady state. Decentralized economy with no-shielding (solid line); Decentralized economy with shielding (dash line); Centralized economy (dotted line)

satellites and launches declines over time in response to the increasing collision risk. As the volume of orbital debris increases, the optimal stock of satellites decreases, which in turn reduces the number of launches and increases the number of satellites destroyed. The speed of convergence to the steady state is relatively low, implying a time adjustment of more than 1000 years, driven by the accumulation process of debris. Compared to the initial situation, the steady state the amount of debris and the number of satellites destroyed are higher, while the stock of operational satellites and the number of launches are lower, for all three scenarios. Note that we are using a stationary model with no growth trend; therefore, the steady-state computation is conditioned on the current situation, assuming constant values over time for the exogenous variables.

Table 2 presents the steady-state values of the key variables in the model across the three scenarios analyzed. Each scenario corresponds to a distinct strategy for satellite deployment and orbital debris management. In the no-shielding scenario, there is no investment in protective measures against collisions, resulting in a steady-state orbital debris stock approximately 100 times greater than its initial level. Consequently, the number of satellites destroyed by collisions is significantly higher than in the alternative scenarios that incorporate some form of shielding, even though the total number of satellites remains comparatively low. Notably, the absence of shielding leads to a substantial reduction in the steady-state number of operational satellites, highlighting the long-term vulnerability of satellite fleets in the absence of mitigation efforts.

Table 2 Steady state values

Variable	No-shielding	Shielding	Central planner
Satellites	7316	7927	7866
Launches (satellites)	1186	1256	1233
Destroyed satellites	89	67	53
Debris	9.7×10^7	7.56×10^7	6.18×10^7
Shielding rate	0.000	0.108	0.125
Value function	15,933.1	17,023.2	17,499.0

This table reports steady-state outcomes for the number of operational satellites, annual launches, collision-related satellite losses, the total stock of orbital debris, the shielding rate, and the value function. Results are shown for three scenarios: a market economy without shielding (no-shielding), a market economy with shielding (shielding), and a centralized economy (central planner)

In contrast, the firm-level shielding scenario supports a larger number of operational satellites, indicating that private investment in protective technologies enhances satellite survivability and slows debris accumulation. The social planner scenario yields an intermediate outcome in terms of satellite count but demonstrates a more efficient balance between shielding and launch activity. This suggests that centralized coordination enables the internalization of the negative externality associated with debris generation, leading to improved long-term sustainability of orbital operations.

The amount of orbital debris is significantly lower in both the firm-level shielding and central planner scenarios compared to the no-shielding case, underscoring the effectiveness of both market-based protective measures and coordinated strategic planning in mitigating debris generation. The number of satellites destroyed by collisions is lowest under the central planner scenario, followed by the firm-level shielding scenario, with the highest destruction rate observed in the absence of shielding. Shielding not only reduces satellite losses but also curtails the emission of debris fragments resulting from collisions. The value function can be interpreted as a measure of the social welfare. These results suggest that implementing shielding, whether as a private profit-maximizing decision or as part of a socially optimal strategy that internalizes the externality, significantly improves the operational capacity of satellite fleets while simultaneously reducing both debris accumulation and satellite attrition.

We identify three main findings. First, in the steady state, both the number of operational satellites and the launch rate are higher in the shielding scenario compared to the no-shielding case. This outcome is driven by a reduced risk of satellite destruction in the event of a collision, owing to the protective effect of shielding. The optimal shielding rate is calculated at 0.108, meaning that approximately 10.8% of collisions are absorbed by the shield, thereby preventing spacecraft fragmentation. Consequently, only 89.2% of collisions result in debris generation. This reduction in vulnerability leads to a lower number of satellites destroyed by collisions relative to the no-shielding scenario. As a result, the steady-state debris population is significantly reduced by approximately 22% due to the decrease in debris emissions from collision events. Importantly, we find that the optimal level of shielding is an increasing function of the collision risk, which itself depends on the stock of orbital debris. Firms' shielding decisions, although guided by profit-maximization, contribute to a reduction in debris accumulation and support a higher number of operational satellites than would occur in the absence of shielding. This represents a clear case of partial private internalization of a negative externality: while shielding is adopted for private benefit, it also generates a positive externality by mitigating the emission of additional debris during collisions.

Second, in a centralized economy where a social planner fully internalizes the negative externality by selecting the optimal level of shielding, the steady-state number of satellites and launches is lower than in the decentralized shielding scenario but remains higher than in the no-shielding case. In this setting, the optimal shielding rate increases to 0.125. When compared to the rate in the decentralized shielding scenario, this suggests that the private internalization of the externality, driven by profit-maximizing decisions of spacefaring firms, is only partial. Full internalization of the social cost of orbital debris necessitates a higher level of shielding. Typically, in decentralized markets, the social costs of externalities are not reflected in individual decision-making. However, the nature of orbital debris generation and its associated damages leads to a degree of partial internalization in this context. On one hand, debris emissions function as a form of self-externality: they are generated by firms operating in the sector and impose costs primarily within the same industry. On the other hand, the resulting damages often manifest as the destruction of firms' own space capital assets. Thus, the negative externality disproportionately affects the very agents responsible for its creation. Because orbital debris directly reduces the profitability of space operations, both immediately, through the destruction of satellites, and over time, via diminished productive capacity, firms have a direct incentive in mitigating its effects. This dynamic provides a rationale for why profit-maximizing firms may engage in behavior that partially internalizes the social cost of orbital debris: they bear a substantial portion of the long-term consequences of space pollution.

Third, in the steady state, the central planner's solution yields a higher optimal level of shielding, which results in a further reduction in both the orbital debris population and the number of satellites destroyed by collisions. However, this outcome is accompanied by a lower number of operational satellites compared to the decentralized economy. This trade-off underscores that privately determined shielding levels, driven by profit-maximization, achieve only a partial internalization of the negative externality associated with space debris. Nevertheless, it is noteworthy that the optimal shielding rate observed under decentralized decision-making does not differ substantially from that in the centralized case. This finding suggests that a significant portion of the social cost associated with orbital debris is internalized by spacefaring firms, owing to the direct impact of debris on their capital assets and long-term profitability.

As a sensitivity analysis, we examine the impact of shielding costs on the steady-state characteristics of the orbital environment. Table 3 presents the steady-state outcomes for both the centralized and decentralized scenarios under alternative values of the shielding cost parameter. The baseline shielding cost is calibrated to reflect current estimates based on the existing number of operational satellites and the orbital debris population. However, this cost is expected to decline in the future due to advancements in spacecraft manufacturing and reductions in launch expenses. As noted by Locke et al. (2024), when shielding is incorporated at the design stage, its

Table 3 Steady state for alternative values of the shielding cost

	$\phi = 0.02$		$\phi = 0.035$		$\phi = 0.05$	
	Decentr	Centralized	Decentr	Centralized	Decentr	Centralized
Satellites	9902	9845	9200	9122	8557	8482
Launches	1497	1486	1409	1392	1330	1310
Destroyed	11	9	29	23	47	37
Debris	2.18×10^7	1.97×10^7	3.87×10^7	3.31×10^7	5.60×10^7	4.68×10^7
Shield rate	0.579	0.615	0.35	0.381	0.219	0.242
Value function	19,937.5	20,232.6	19,265.4	19,861.8	18,187.5	18,664.1

This table compares steady state values for the number of satellites, launches, destroyed satellites by collision, number of orbital debris, shielding rate, and the value function for the market economy where firms choose the optimal shielding rate (Decentr.) with the social planner solution (Centralized)

installation cost may become negligible. Moreover, the substantial decrease in per-kilogram launch costs over recent decades further contributes to the declining cost of shielding, as added mass becomes less economically burdensome. To explore the implications of these trends, we compute steady-state outcomes using three alternative values of the shielding cost parameter ($\phi = 0.05$, 0.035, and 0.02).

As the cost of shielding decreases, the level of protection increases, leading to reductions in both the number of satellites destroyed by collisions and the overall debris population. Lower shielding costs correspond to higher optimal numbers of satellites and launches. Despite this increase in satellite numbers, the debris population declines because, for a given collision probability, fewer satellites are destroyed, thereby reducing debris emissions from collisions. Consistent with expectations, the optimal level of shielding is higher in a centralized economy, where the externality is fully internalized, compared to a decentralized economy. This results in fewer satellites destroyed and a smaller debris population, albeit at the cost of a reduced total number of satellites. For instance, when the shielding cost parameter is 0.02, the optimal shielding level rises to 0.579 and 0.615 in decentralized and centralized economies, respectively. A key finding is that the steady-state outcomes under the decentralized scenario closely approximate those of the centralized planner. As shielding costs decline, the optimal shielding levels in both settings converge, indicating that the decentralized solution approaches the socially optimal first-best outcome. This convergence arises because this specific negative externality directly impacts both firms' space capital stock and profits, given that collision risks not only reduce current profits but also negatively affect future profitability.

5 Discussion of results

The results presented in the previous section carry significant implications for space sustainability, strategic decision-making by private firms regarding satellite design, and policy-makers. We examine each dimension below.

5.1 Implications for space sustainability

Our findings provide clear evidence that satellite shielding plays a crucial role in enhancing the long-term sustainability of orbital operations. By reducing both the probability of satellite destruction and the debris generated per collision, shielding mitigates the self-reinforcing accumulation of debris characteristic of the Kessler syndrome. In both decentralized and centralized scenarios, shielding leads to lower steady-state debris stocks and higher numbers of operational satellites, illustrating that technological improvements at the firm level can substantially slow the degradation of the orbital commons.

The model also demonstrates that even when firms act independently, market incentives generate a degree of partial internalization of the externality. Because debris imposes direct losses on the firms generating it, profit-maximizing operators are naturally incentivized to adopt mitigation and protective measures. This mechanism distinguishes the space economy from many typical terrestrial pollution scenarios, where damages often accrue to third parties. Nevertheless, equilibrium shielding in the decentralized economy remains below the socially optimal level, highlighting the need for coordination to bridge this efficiency gap and underscoring the importance of regulatory policies that encourage shared standards and cooperative action.

5.2 Implications for space firms strategy

For commercial operators, shielding is not merely a regulatory requirement but a strategic measure to protect assets. Firms that integrate shielding during satellite design enhance longevity, reduce replacement costs, and stabilize revenue streams in debris-dense orbits. As launch and manufacturing costs continue to decline, the relative cost of shielding diminishes, making higher protection levels economically optimal. Simulation results suggest that lowering shielding costs brings decentralized outcomes closer to the social optimum, highlighting the role of technological innovation, such as advanced materials, modular satellite architectures, and lightweight protective solutions, in aligning private profitability with collective sustainability.

These findings also point to potential market differentiation based on durability and reliability. Operators adopting higher protection standards may benefit from reduced insurance premiums, creating additional incentives for sustainable practices. As orbital congestion increases, investment in shielding may become a prerequisite for firms seeking long-term competitiveness in crowded constellations.

5.3 Implications for policy and governance

From a space global policy perspective, the results draw attention to the need for mechanisms that internalize the remaining externality gap between private and socially optimal shielding. Possible approaches include: (i) Establishing minimum shielding standards and certification for specific orbital regimes; (ii) Implementing fiscal incentives such as subsidies or tax credits for enhanced protection technologies or R&D in shielding materials; and (iii) Developing liability and insurance frameworks that price orbital risk according to expected contributions to debris, rewarding operators who adopt mitigation measures.

Because shielding generates positive spillovers by reducing debris for all orbit users, coordinated international governance, through institutions such as the UN Committee on the Peaceful Uses of Outer Space (COPUOS) or industry-led consortia, can enhance efficiency. Policies aimed at lowering shielding costs, for example through technology transfer or standardization, may also help decentralized markets approach the social optimum identified by the model.

Overall, technological and institutional innovation are complementary. While private shielding measures reduce debris accumulation, long-term orbital sustainability requires governance structures that ensure alignment between individual incentives and global welfare. The increasing participation of private actors in space calls for economic instruments and cooperative norms that reward proactive stewardship of the orbital environment.

6 Concluding remarks

This paper examines the economic and environmental implications of satellite shielding implemented by spacefaring operators. Orbital debris generated by space activities poses a significant threat to spacecraft, which can be destroyed upon collision with debris fragments. To mitigate this risk, space operators may employ shielding effective against small debris or implement collision avoidance systems designed to evade larger, trackable debris. Both forms of protection not only reduce spacecraft losses but also contribute to lowering the generation of additional debris.

Our focus in this study is on shielding, which exemplifies a partial internalization of a negative externality within a decentralized economy. Firms generate a negative externality that adversely impacts their own capital stock, i.e. operational satellites. In this context, optimal decisions by individual firms can yield positive social welfare outcomes by mitigating debris generation. The model developed here considers an unregulated orbital market, where outer space functions as a global commons subject to negative externalities in the form of space debris. This debris, produced by satellite launches and in-orbit collisions, poses hazards that can destroy operational satellites.

Using a calibrated model, we analyze alternative scenarios. As anticipated, the negative externality reduces market activity, resulting in fewer satellites as firms factor in expected losses from collisions. Greater debris accumulation corresponds to fewer operational satellites. We then examine the strategy of enhancing passive defenses through shielding in both decentralized and centralized economies. In the decentralized setting, shielding represents an individual firm's response to collision risk, which simultaneously exerts a positive external effect by reducing debris generation. While shielding entails additional costs, it lowers the probability of satellite destruction and diminishes debris emissions from collisions. Notably, our results indicate that the steady-state equilibrium in the decentralized economy closely approximates the centralized planner's solution, suggesting that although the profit-maximizing strategy of spacefaring firms is socially suboptimal, it remains near the first-best outcome.

A similar analysis can be applied to examine the implications of collision avoidance systems. Unlike shielding, which protects against small debris that cannot currently be tracked, collision avoidance targets larger debris fragments that can be tracked and for which conjunction probabilities can be calculated. The same principles of partial internalization of the negative externality, driven by firms' profit-maximizing behavior within a decentralized framework, apply. Collision avoidance not only preserves space capital assets but also helps reduce the endogenous generation of debris in orbit. For firms, the key decision involves weighing the costs of executing collision avoidance maneuvers against the benefits of maintaining the satellite's operational status.

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Declarations

Conflict of interest The authors have no Conflict of interest or financial interests to disclose.

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