Commercial Space Expansion under Economic Kessler Syndrome: Evaluating Orbital Sustainability-Utilization Trade-offs under a Launch Tax–ADR Policy

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Abstract

As large-scale satellite constellation deployment accelerates and orbital congestion risk rises, a key governance question for space sustainability is whether rapid launch growth can be managed without persistent debris accumulation. This study develops a system dynamics model to examine how future launch-growth scenarios, the Economic Kessler Syndrome (EKS) loop, and a combination of launch tax and active debris removal (ADR) policy interact over time. Three launch-growth scenarios are introduced to compare reference and policy cases in terms of debris accumulation, expected launch demand, fiscal burden, and orbital utilization. The results indicate that governance regimes matter more than growth pressure alone in determining the long-run debris trajectory: in the reference cases, debris continues to accumulate, whereas in the policy cases, it peaks early and declines across all scenarios. The simulations also show that strong debris reduction does not necessarily imply lower long-run utilization, although the fiscal burden required to sustain such improvement rises sharply with stronger launch-growth pressure. The study suggests that space sustainability, fiscal burden, and utilization are shaped jointly by the underlying governance design, and clarifies the dynamic trade-offs and the major feedback that future institutional design must address.

Keywords: orbital debris; satellite constellation programs; space sustainability; system dynamics; governance; active debris removal (ADR); Kessler Syndrome; Economic Kessler Syndrome (EKS).

1 Introduction

1.1 Background and Problem

Earth orbit is a globally shared common resource that underpins navigation, telecommunications, weather forecasting, disaster warning, Earth observation, and digital synchronization. These satellite-

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based services support a wide range of public and private commercial activities on the ground, and the scale of dependence is already economically significant (OECD, 2024). It is estimated that the combined loss of GPS navigation and timing services alone could impose losses of at least 1 billion dollars per day on the U.S. economy (NIST, 2019). In this sense, Earth orbit is not merely a technical domain for satellites but an invisible infrastructure layer of the global economy.

At the same time, this vital orbital environment is becoming increasingly hazardous. NASA's 2025 orbital-debris chart (Figure 1) shows a continuing increase in the cataloged population of objects. Operational data also indicate that congestion-related risk is intensifying. SpaceX's Starlink satellites conducted 144,404 collision-avoidance maneuvers in the first half of 2025 alone, roughly three times the rate of the previous six months (O'Callaghan, 2025). Furthermore, NASA reports that by 2025 the International Space Station (ISS) had conducted a total of 41 collision-avoidance maneuvers since 1999 (NASA, 2025).[1] These trends suggest that the frequency of conjunction warnings and avoidance pressure has accelerated sharply in recent years, even if the number of actual avoidance maneuvers varies between spacecraft types and operational contexts.

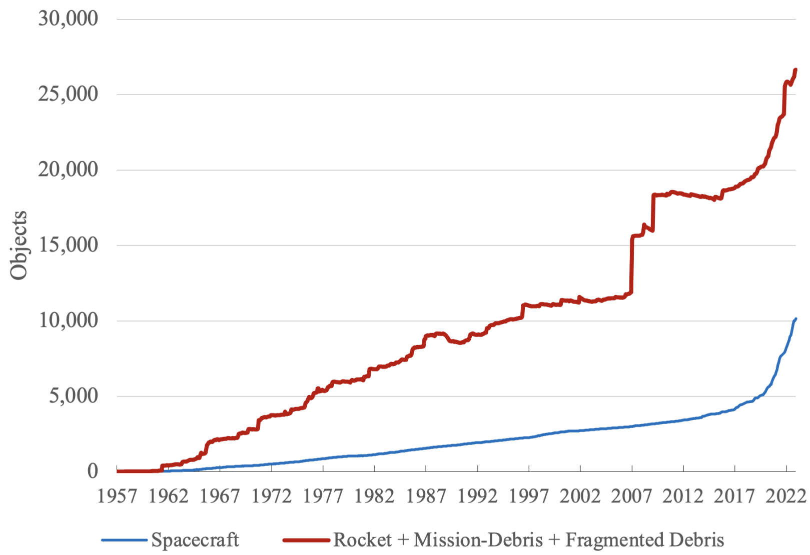


Figure 1: Number of tracked objects in Earth orbit by object type (NASA, 2025). Stacked graph.

The problem is no longer limited to orbit. Following the 2024 breakup of the Russian RESURS-P1 satellite, ISS astronauts were temporarily ordered to shelter, illustrating the operational consequences of large breakup events in already congested orbital regions (U.S. Space Command, 2024; Roulette, 2024). On the atmospheric side, Wright et al. (2025) estimate that the world's highest-density airport-centered airspace regions face an annual probability of about 0.8% of being affected by an uncontrolled rocket-body reentry, indicating that airspace disruption risk is measurable even where direct strike probabilities remain low.

[1] The ISS figure refers to actual collision-avoidance maneuvers (CAMs), not to the much larger number of conjunction warnings or conjunction data messages (CDMs). Thus, the relatively modest cumulative number of ISS maneuvers should not be interpreted as evidence of low conjunction pressure, especially given the rapid recent increase in warning frequency and avoidance activity across commercial satellite constellations.

Figure 1 should therefore be read not only as a count of objects but also as evidence of persistence of the underlying problem. Objects inserted into orbit do not disappear quickly. Vanguard 1, a grapefruit-sized scientific satellite launched in 1958, still remains in orbit today. As of 1970, its remaining orbital lifetime was estimated at roughly 240 years (Green and Lomask, 1970), making it the oldest human-made object still orbiting Earth. More generally, orbital lifetimes increase sharply with altitude, and objects in heavily used regions in low-earth orbit (LEO) can remain in orbit for decades, centuries, or longer if left unmanaged (NASA, 2019).[2]

Under such persistent conditions, object accumulation is not a transient inconvenience, but a structural source of long-term risk. This was precisely the logic behind the Kessler Syndrome hypothesis: once object density becomes sufficiently high, collisions can generate additional debris, which in turn raises the probability of further collisions, creating a self-reinforcing deterioration of the orbital environment (Kessler and Cour-Palais, 1978). Adilov et al. (2018) further analyzed that the current incentive structure can generate what they call *Economic Kessler Syndrome* (EKS), in which worsening debris conditions render further orbital use increasingly less attractive and economically self-undermining.

A central reason why this problem has been postponed is policy misalignment. Current debris mitigation frameworks are important but remain largely non-binding under international law. Both the United Nations Space Debris Mitigation Guidelines and the Long-term Sustainability Guidelines are voluntary instruments, and their implementation depends heavily on national or organizational uptake (UNOOSA, 2010, 2021). At the same time, the environmental costs of congestion, collision risk, and future remediation are distributed across many users and jurisdictions, while the benefits of launches are often private and immediate. This creates a familiar common-pool-resource problem in which actors do not fully internalize the environmental costs they impose on others.

This growing concern is also reflected in recent institutional initiatives. The ESA's Zero Debris approach explicitly aims to significantly limit the production of debris in Earth and lunar orbits by 2030 for future missions, programs, and activities, and its Zero Debris Charter seeks to broaden this ambition into a wider collective commitment (ESA, 2023, 2024). These initiatives indicate that the effort is moving beyond the narrow mitigation toward a more ambitious vision of zero-debris-oriented stewardship. At the same time, they do not by themselves resolve the question of how such ambitions are to be financed and sustained under continuing commercial expansion.

A related challenge is the mismatch between technology investment and institutional adoption. Active debris removal (ADR) is no longer purely conceptual. ESA has already procured ClearSpace-1 as the first commercial mission intended to remove a piece of debris from orbit (ESA, 2020), and the JAXA's CRD2/ADRAS-J program has demonstrated close-proximity inspection of an actual derelict object (H-IIA upper stage rocket) through rendezvous and proximity operations (JAXA, 2024). NASA's recent cost–benefit assessments also show that debris remediation can be economically meaningful under some conditions (Locke et al., 2024). Yet the existence of technical capability does

[2]See also Diserens (2022, Fig. 2.7) for an adapted contour-style presentation of orbital lifetime by altitude based on NASA reference guide. For a representative debris object with an area-to-mass ratio of 0.01 m^2/kg, the figure shows a strong nonlinear increase in persistence with altitude: near-circular orbits at a few hundred kilometers typically decay within years or less, whereas objects around 700–900 km can remain in orbit for decades to centuries, and those near or above 1,000 km may persist for much longer. For eccentric orbits, lifetime depends strongly on perigee altitude because atmospheric drag is concentrated near perigee.

not automatically produce large-scale deployment. The reason is not only technical uncertainty, but also incentive misalignment: those who can remove debris are not necessarily those who create it, and those who suffer from congestion are not necessarily those with a direct incentive to finance ADR.

This incentive misalignment reflects a more fundamental problem: the orbital environment functions as a common pool resource subject to open-access exploitation, in which congestion and debris arise from externalities, weak coordination, and insufficient governance rather than from technical growth alone (Ostrom, 1990; Salter, 2016). The non-appropriation principle established by the Outer Space Treaty effectively induces open-access conditions, under which operators impose collision risks on one another without internalizing the costs (Rao and Rondina, 2025). Similar dynamics have been documented in terrestrial commons such as fisheries and atmospheric pollution, where the absence of clearly defined usage rights leads to over-exploitation even when individual actors behave rationally (Ostrom, 1990).[3]

These misalignments have motivated a growing body of economic policy proposals for orbital-environment management. Rao et al. (2020) showed that orbital-use fees can substantially increase the long-term value of the space industry by internalizing congestion externalities. Other studies have examined deposit-refund systems, performance bonds, launch-related taxation, and other market-based instruments to align private incentives with collective orbital sustainability (Buchs and Bernauer, 2023; Ni et al., 2024).

Along similar lines, Minato and Yamaguchi (2025) developed a system dynamics framework to examine a combination of launch tax and ADR financing policy and showed that a Space Environmental Tax (SET) can reduce debris accumulation by discouraging excessive launches while simultaneously generating financial resources for debris removal. Their results also suggested that dynamically adjusted tax rates could function as a resilient governance mechanism that responds to orbital congestion. However, their model lacks congestion-driven behavioral feedback and analysis. We therefore still understand relatively little about how future launch expansion, endogenous congestion-driven contraction, and tax-financed ADR interact dynamically over long time horizons.

1.2 Purpose

A common intuition is that a stronger environmental intervention, such as launch taxation, may be incompatible with continued commercial expansion in orbit. Yet unmanaged growth can itself intensify orbital congestion, increase collision risk, and eventually induce a contraction in launch activity and orbital utilization (as suggested by the Economic Kessler Syndrome proposition). This raises a more fundamental problem for orbital-environment governance: the challenge is not simply whether to reduce debris, but how to manage the trade-off among orbital sustainability, continued utilization of space, and the fiscal feasibility and operability of intervention.

The earlier model developed by Minato and Yamaguchi (2025) established a policy framework to examine how launch taxation and ADR subsidies could mitigate debris accumulation. However,

[3] In this paper, the term *governance regime* is therefore used in a broad institutional sense to include both unmanaged open-access conditions and explicit policy-based intervention, since the absence of orbital-environment policy is itself a collective choice about an institutional condition with long-run consequences.

that earlier version primarily examined historical-period what-if comparisons and represented launch-demand adjustment mainly through the price channel. Reviewer feedback also highlighted the need for future-period policy testing, multiple strategic settings, and endogenous operator responses under worsening orbital conditions. These issues have become more pressing as commercial launch growth accelerates and the orbital environment becomes more congested.

Consequently, the purpose of this paper is not merely to revisit whether launch taxation can reduce debris. Rather, it is to examine whether a launch tax–ADR regime can still function as a meaningful governance instrument under future launch expansion and under the possibility of endogenous, congestion-driven contraction in space activity itself. Put differently, the paper asks whether taxation should be understood only as a burden on growth, or whether it may instead be part of the institutional conditions required for growth to remain governable over the long run.

1.3 Research Questions

Against this background, this study asks three related questions.

1. Can future launch expansion remain viable, or will rising congestion eventually suppress launch demand?
2. Can a Launch Tax–ADR (LT–ADR) policy mitigate debris growth without making future orbital utilization fiscally or politically unmanageable?
3. Do long-run orbital outcomes depend more on the magnitude of launch-growth pressure itself, or on the governance regime under which that growth occurs?

To address these questions, the present paper extends the earlier system dynamics model presented by Minato and Yamaguchi (2025) in four ways. First, the simulation horizon is extended from the 1957–2022 historical validation period used in the earlier model to 2075, with the historical calibration updated through 2025, in order to examine future policy performance under a fixed-year (*e.g.*, 50-year) debris-removal target horizon. Second, a simplified EKS-motivated balancing loop is introduced to represent voluntary launch contraction under worsening orbital conditions. Third, three alternative future launch scenarios are added to represent constant, announced-plan-based, and high-expansion trajectories. Fourth, the formulation of the debris-removal target is revised to support forward-looking policy experiments under a zero-debris-oriented policy objective. This target should be understood as a stylized stock-reduction formulation for long-run policy experiments, rather than as a literal implementation of ESA's preventive Zero Debris initiative.

The paper then examines how these model revisions alter the interpretation of launch taxation, ADR policy, and the long-term relationship between orbital sustainability and orbital utilization.

Structure of the Paper

The remainder of the paper is structured as follows. Section 2 develops the dynamic hypothesis and visualizes its feedback structure. Section 3 explains the model design and the main revisions introduced for the present study. Section 4 sets out the simulation assumptions and reports the results of the model validation and historical calibration. Section 5 presents the simulation results, while Section 6 discusses their interpretation, policy implications, and limitations.

2 Dynamic Hypothesis

Figure 2 summarizes the dynamic hypothesis of the present study. The orbital environment is governed by the interaction between self-reinforcing debris accumulation, endogenous behavioral responses by launch operators, and policy-based mitigation through launch taxation and active debris removal (ADR). The figure is based on the causal-loop structure presented by Minato and Yamaguchi (2025), but the present study explicitly separates and highlights the balancing feedback associated with congestion-driven voluntary launch contraction, or B1 loop.

At the core of the system is the familiar reinforcing loop R1, corresponding to the Kessler Syndrome mechanism (Kessler and Cour-Palais, 1978). As the number of objects and debris in orbit increases, the perceived risk of collisions related to congestion increases. Higher collision risk leads to more collision events and fragmentation, which in turn generates additional debris and further worsens the orbital environment. This reinforcing mechanism captures the fundamental physical logic by which orbital congestion can become self-amplifying over time.

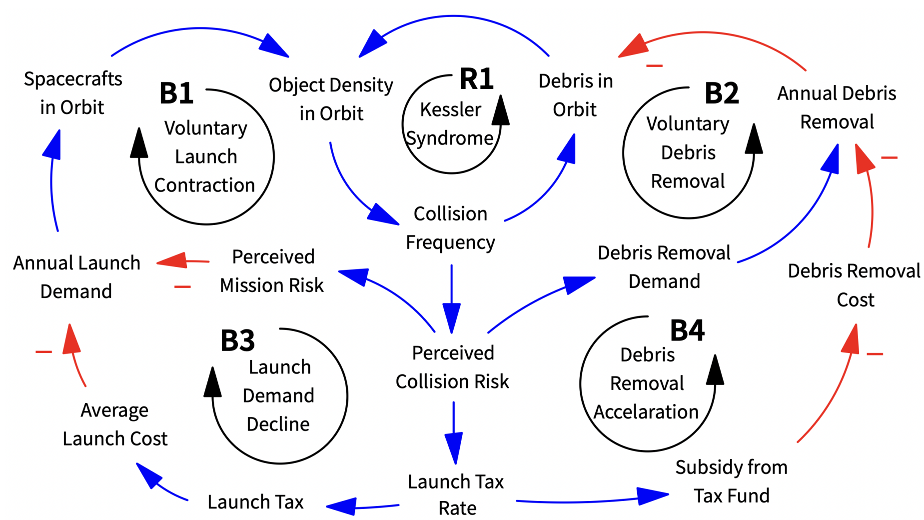


Figure 2: Causal loop diagram of orbital congestion, endogenous launch contraction, and policy intervention. The diagram highlights the reinforcing debris-accumulation (R1), the EKS-related voluntary launch-contraction loop (B1), and the balancing policy feedbacks associated with launch taxation and ADR. Adapted from Minato and Yamaguchi (2025, Fig.2), with minor revisions.

Our model extends this framework by introducing a simplified balancing loop B1, interpreted as an EKS-related voluntary launch-contraction mechanism. As perceived collision risk increases, launch operators are assumed to revise the expected launch demand downward, reflecting growing concern about the deteriorating orbital environment and the declining commercial attractiveness of orbital use under congested conditions. Lower expected launch demand leads to fewer launches and thus reduces the inflow of spacecraft and launch-related debris. In this way, worsening orbital conditions may generate an endogenous brake on further launch expansion. This loop is conceptually related to the Economic Kessler Syndrome discussed by Adilov et al. (2018), although the present model represents it in a simplified behavioral form presented in Section 3.

The model also retains the main policy feedback from the earlier framework by Minato and Yamaguchi (2025). First, the introduction of launch tax affects launch demand through the price channel: a higher required tax rate raises launch costs and restrains expected launch demand. This mechanism constitutes a balancing policy loop, since higher launch activity and debris burden eventually induce stronger policy pressure, which then dampens future launch activity. Second, launch taxation generates fiscal resources for ADR, which reduces the stock of debris and partially counteracts the reinforcing debris-growth mechanism. This second policy feedback is likewise balancing in nature, since worsening orbital congestion increases the pressure for debris removal, and debris removal in turn works to lower future object density and space traffic congestion.

Taken together, these loops imply several expected patterns of behavior. Without effective policy intervention, continued launch growth is expected to increase orbital debris and congestion risk over time. The newly added B1/EKS loop may partially offset this trend by generating endogenous contraction in launch demand. However, contraction is reactive and occurs only after orbital conditions have already deteriorated.[4] By contrast, launch taxation and ADR operate as explicit governance mechanisms that attempt to moderate the debris-growth process more directly.

The central dynamic hypothesis of this paper is, therefore, that long-run orbital outcomes are shaped not only by the magnitude of exogenous launch-growth pressure, but also by the interaction between endogenous congestion-driven contraction and policy-based debris management. More specifically, the present study expects three broad outcomes. First, future launch-growth scenarios define the level of potential expansion pressure, but realized launch demand will deviate from these reference paths once congestion-driven contraction and policy intervention are introduced. Second, the EKS-related balancing loop may reduce debris growth to some extent by restraining launch demand, but it may also reduce the tax base available for debris-management policy. Third, the combined presence of endogenous launch contraction and policy intervention may generate better environmental outcomes than either mechanism alone, while also revealing trade-offs between orbital sustainability, orbital utilization, and fiscal stability and feasibility. These expectations are evaluated in the simulation experiments reported in the following sections.

[4] Importantly, reducing or even eliminating the inflow of newly launched objects does not necessarily halt debris growth. Once the existing orbital population becomes sufficiently collision-prone, collisions among objects already in orbit can continue to generate fragments, allowing the reinforcing R1 loop to remain dominant even after the balancing B1 loop suppresses new launch activity. The CLD represents the polarity and structural interaction of these feedbacks, with each causal link interpreted *ceteris paribus*, but it does not by itself determine their time-dependent relative dominance, delays, nonlinear thresholds, or resulting behavior. These properties must therefore be evaluated through the stock–flow formulation and simulation.

3 Model Design

3.1 Overview of the Model Structure

Figure 3 provides a schematic overview of the model architecture. The present model retains the basic stock-flow architecture developed by Minato and Yamaguchi (2025), while extending it to support forward-looking policy experiments under future launch-growth conditions. As in the previous framework, the model is designed as a stylized source-sink representation of orbital congestion and debris management rather than as a high-fidelity orbital debris evolutionary model.[5] Its purpose is to capture the long-term interaction among launch activity, debris accumulation, and policy intervention at the highly aggregated level.

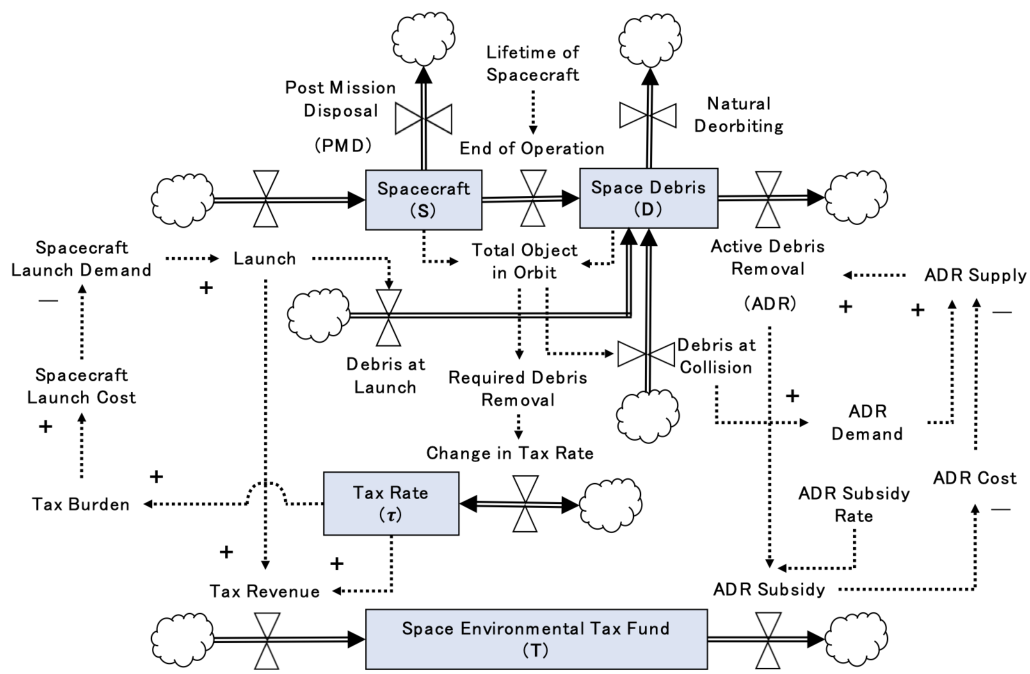


Figure 3: Schematic overview of the system dynamics model. The figure summarizes the main stocks, flows, and policy linkages. Note that it does not reproduce the full stock-flow diagram, which is too large and detailed to be presented legibly in the main text. Therefore, some arrows represent physical flows, while others represent monetary or informational linkages. The schematic connections should be read as indicating causal and accounting relationships among model components, not as direct unit-to-unit conversions among variables. Adapted from Minato and Yamaguchi (2025, Fig.3).

The model focuses on two principal stocks: the number of spacecraft in orbit and the number of space debris in orbit. Spacecraft enter orbit through launches and leave through natural deorbiting after mission completion, while debris accumulates through launch-related generation and collision-related fragmentation and is reduced through natural deorbiting and active debris removal (ADR). On the policy side, a launch-tax mechanism is used to generate financial resources for ADR, thereby

[5]See Lee et al. (2024) for different types of debris evolutionary models developed among major space agencies.

linking orbital congestion to both launch incentives and debris-removal activity.

This structure allows the model to represent three connected dimensions of orbital-environment governance. First, it captures the physical persistence of orbital objects, including debris. Second, it links orbital congestion to economic activity through launch demand and launch pricing. Third, it represents debris management as a financially mediated policy process in which the burden of remediation depends on both the scale of the debris problem and the size of the launch base subject to taxation. The main contribution of the present paper lies not in a complete redesign of this architecture, but in a set of model revisions that enable future-period analysis under launch expansion, endogenous launch contraction, and revised zero-debris-oriented policy targeting described below.

3.2 Main Extensions in the Present Study

To address the research questions discussed in Section 1.3, the present study modifies the previous launch tax–ADR framework in four main respects: (1) extension of the simulation horizon from the historical period to 2075, (2) addition of future launch demand scenarios, (3) introduction of a simplified EKS-related voluntary launch-contraction mechanism to study its effect on the orbital environment, and (4) revision of the debris-removal target formulation for zero-debris-oriented policy experiments. Since the baseline stock-flow logic has already been presented by Minato and Yamaguchi (2025), the following subsections focus only on the revised components most relevant to the present analysis.

3.2.1 Extension of the Simulation Horizon and Future Launch Scenarios

The first revision is the extension of the time horizon from the historical period (1957-2025) to 2075. This is necessary because the debris-removal policy target is defined over a fixed-year (50-year in the baseline) management horizon, making a longer forward-looking period essential for evaluating the timing and consequences of orbital-environment intervention. The second revision introduces three future launch scenarios. These scenarios are not intended as forecasts, but as stylized trajectories representing different levels of launch-expansion pressure after the historical period. Specifically, scenario 1 assumes that the annual number of successful orbital launches remains constant at the 2025 level. Scenario 2 represents an announced-plans scenario based on publicly known satellite deployment programs and a front-loaded build-out pattern. Scenario 3 represents a more aggressive expansion path in which launch activity remains persistently higher than the announced-plans.

In the model, future launch activity is represented through a reference-demand path and the average number of spacecraft per launch. Accordingly, future launch-growth pressure is specified exogenously, while realized launch demand remains endogenously affected by pricing and congestion-related feedback.

$$L_t^{\text{ref}} = \begin{cases} \bar{L}, & \text{Scenario 1} \\ \bar{L} + L_t^{\text{inc}}, & \text{Scenario 2 or 3} \end{cases} \tag{1}$$

$$L_t^{\text{inc}} = \frac{D_t^{\text{inc}}}{s_t} \tag{2}$$

Here, L_t^{ref} denotes the future launch-demand reference, $\bar{L}$ the baseline future launch level, L_t^{inc} the incremental launches required, D_t^{inc} the future incremental spacecraft deployment, and s_t the average number of spacecraft per launch.

3.2.2 EKS-Related Voluntary Launch Contraction

The third major revision is the introduction of a simplified EKS-related balancing mechanism. In the previous model, the launch demand changed only through the launch-price channel. In the present version, expected launch demand is also allowed to respond to worsening orbital conditions. This captures the possibility that launch operators (or their clients) may become more cautious as the orbital environment deteriorates.

$$L_t^{\mathrm{exp}} = L_t^{\mathrm{ref}} \cdot P_t \cdot R_t \tag{3}$$

where L_t^{exp} denotes expected launch demand, P_t is the effect of launch price on launch demand, and R_t is the effect of collision risk on launch demand.

The collision-risk effect is represented through a debris-based risk proxy rather than a directly estimated collision probability. This is consistent with the interpretation of the EKS loop introduced in the present study as a stylized behavioral response to worsening orbital conditions.

$$R_t = \begin{cases} 1, & t \leq 2025 \\ (Q_t)^{-\varepsilon_r}, & t > 2025 \end{cases} \tag{4}$$

Here, Q_t is the selected collision-risk proxy for launch demand, and ε_r is the elasticity of launch demand with respect to perceived collision risk.

To examine the sensitivity of this behavioral mechanism, the model allows three alternative risk proxies to be selected through a switch variable: debris stock, total tracked objects in orbit, and debris share in orbit. These alternatives represent, respectively, risk perception based on the absolute debris burden, the overall congestion level in orbit, and the relative composition of debris within the tracked orbital population. The default specification adopts the debris-stock proxy, because debris is interpreted as the most persistent and least controllable collision hazard. For elasticity, $\varepsilon_r = 0.3$ is adopted as a conservative stylized assumption. This parameter is not intended as an empirically calibrated coefficient, but as a moderate behavioral parameter that activates the newly introduced balancing loop without dominating the launch demand dynamics.

3.2.3 Revised Zero-Debris-Oriented ADR Target and Tax Requirement

The fourth revision concerns the debris-removal target and the associated tax requirement. In the present model, the required tax rate is adapted to support zero-debris-oriented management over the extended future horizon. Specifically, rather than relying only on a fixed (number of) annual removal target, the model includes a stock-zeroization-oriented target formulation that adjusts debris-removal demand in relation to both existing debris stock and ongoing net inflows as follows:

$$A_t^{\mathrm{req}} = \max\left\{0,\ A_t^{\mathrm{base}} + (G_t - N_t)\right\} \tag{5}$$

where A_t^{req} is the required ADR for stock-zeroization, A_t^{base} is the annual debris-removal target (which is introduced in the earlier model by Minato and Yamaguchi 2025), G_t is gross debris inflow, and N_t is natural deorbiting.[6] For clarity, gross debris inflow G_t is defined as the total annual addition to the debris stock from both launch-related sources and collision-driven fragmentation. In the revised model, it is expressed as follows:

$$G_t = G_t^{\mathrm{L}} + G_t^{\mathrm{C}} \tag{6}$$

where G_t^{L} denotes launch-related debris inflow, and G_t^{C} denotes collision-generated debris inflow. This formulation makes explicit that the debris stock is affected not only by routine launch activity but also by the endogenous fragmentation dynamics associated with orbital congestion.

$$A_t^{\mathrm{tar}} = \begin{cases} A_t^{\mathrm{req}}, & \text{if stock-zeroization targeting is used} \\ A_t^{\mathrm{base}}, & \text{otherwise} \end{cases} \tag{7}$$

Here, A_t^{tar} is the ADR policy target selected by the policy switch. In the current specification, however, realized ADR is constrained by the annually fundable amount under the selected funding rule.[7] The policy target is therefore not always fully implementable when fiscal resources are insufficient.

Based on this annual ADR target, the required launch-tax rate τ_t^{req} is determined as follows:

$$\tau_t^{\mathrm{req}} = \max\left\{0,\ \frac{c_t^{\mathrm{ADR}}\,\phi\,A_t^{\mathrm{tar}}}{p_t^{\mathrm{L}}\,L_t^{\mathrm{exp}}}\right\} \tag{8}$$

where c_t^{ADR} is the average price of debris removal per object, ϕ is the ADR subsidy ratio, and p_t^{L} is the average launch price. Equation (8) should be interpreted as yielding a theoretical tax rate required to finance the debris-removal objective under the model assumptions. It does not impose an explicit political or industrial upper bound on taxation. Accordingly, very high values should not be read as feasible policy recommendations, but rather as indicators of the scale of fiscal effort that would be necessary to pursue the stated target mechanically under severe congestion conditions.

[6] It should be noted here that this stock-zeroization-oriented target is not intended as a literal implementation of ESA's Zero Debris initiative briefly mentioned in Section 1. ESA's approach is primarily preventive and mitigation-focused, aiming to significantly limit the creation of new debris from future activities, whereas the present model introduces a stylized remediation-oriented stock target in order to examine the long-run interaction among ADR demand, tax financing, and orbital congestion.

[7] In the current specification, the annual fundable ADR measure is calculated on a subsidy-per-ADR basis rather than on the full average removal cost. This means that the indicator represents how many ADR actions can be supported by the public sector per year when only the subsidized share is publicly financed. The remaining cost is implicitly assumed to be borne by private operators, ADR service providers, or other non-public actors under a cost-sharing arrangement.

3.3 Expected Dynamics in the Revised Model

Based on the revised structure described above, several broad patterns of behavior are expected. Without effective policy intervention, sustained launch growth increases the inflow of spacecraft and launch-related debris, thereby raising the total population of orbital objects and worsening congestion over time. As debris accumulates, collision-related risk increases further, contributing to additional fragmentation and long-run deterioration of the orbital environment.

At the same time, the revised model includes balancing forces that may partially offset this trend. Launch taxation restrains launch demand through the price channel, while the tax revenues generated by launches finance ADR and thereby reduce the debris stock. In the present study, an additional endogenous balancing mechanism is introduced: worsening orbital conditions are assumed to reduce expected launch demand through a simplified EKS-related voluntary launch-contraction.

The resulting behavior is therefore expected to reflect the interaction of three forces: exogenous launch-growth pressure, endogenous congestion-driven contraction, and policy-based debris management. Future launch scenarios define the level of potential expansion pressure, but realized launch demand may deviate substantially from these reference paths once voluntary launch contraction (EKS loop) and policy intervention are introduced. Similarly, debris accumulation may be reduced by either endogenous contraction or policy intervention, but these effects may also generate trade-offs involving orbital utilization and fiscal burden. These expectations are evaluated in the simulation experiments reported in Section 5.

4 Model Parameters and Historical Calibration

4.1 Baseline Parameter Settings

Table 1 summarizes the parameters adopted in the present study. Most parameters are inherited from the earlier model developed by Minato and Yamaguchi (2025), preserving the core structure of the previous framework. The newly added parameters, marked with †, are introduced to support the future-period extensions developed in the present study. The baseline future launch demand is anchored to the 2025 level of successful orbital launches, while the reference values for debris and tracked objects are used to normalize the EKS-related launch-risk proxy, which determines the effect of collision risk on launch demand (as discussed in Section 3.2.2). The elasticity of launch demand with respect to collision risk is adopted as a conservative stylized assumption, not as an empirically calibrated coefficient.

The historical period is defined as 1957–2025 in the extended model. In this paper, this historical simulation is referred to as the historical calibration run, in order to distinguish it from the forward-looking simulation cases examined in the Results section. Historical launch data is introduced as exogenous input based on annual successful orbital launches, using the “launches reaching orbit” series compiled by McDowell (2026). This series is used to drive spacecraft inflow in combination with the calibrated average number of spacecraft per launch. The latter is not interpreted as a directly observed annual average for each year, but as an aggregate calibration parameter chosen so that the model reproduces the long-run evolution of spacecraft stock based on the historical data

Table 1: Parameter settings used in the extended model.

Name of Constants	Values	Units
Initial Number of Spacecrafts	0	Objects
Initial Number of Space Debris	0	Objects
Initial Launch Tax Rate	0	Dmnl
Time to Adjust Tax Rate	2	Year
Target Period of Total Debris Removal	50	Year
Average Spacecraft Operational Lifetime	7	Year
Average Duration to Natural Deorbiting	20	Year
Post Mission Disposal (PMD) Success Ratio	0.3	Dmnl
Average Debris Generation per Launch	3.2	Obj./Launch
Average Debris Generation per Nominal Collision	5	Obj./Collision
Average Debris Generation per Catastrophic Collision	3500	Obj./Collision
Collision Probability	1e-07	Dmnl
Price Elasticity of Launch Demand	0.9	Dmnl
Price Elasticity of Debris Removal Demand	0.9	Dmnl
Average Price of Launch	100	$M/Launch
Average Price of Debris Removal	10	$M/Object
ADR Subsidy Ratio	0.5	Dmnl
Elasticity of Launch Demand with respect to Collision Risk†	0.3	Dmnl
Reference Number of Space Debris for Launch Risk†	18,000	Objects
Reference Number of Tracked Objects for Launch Risk†	32,000	Objects
Baseline Future Launch Demand†	321	Launch/Year

Note: Parameters marked with † were added in the extended model presented in this paper.

for launches. These parameter settings are intended to provide a coherent source–sink model that can reproduce the broad historical evolution of spacecraft, debris, and total tracked objects in Earth orbit and can then be extended to future policy experiments.

4.2 Behavior Reproduction Test

Figure 4 reports the behavior reproduction test for the historical validation period from 1957 to 2025. Because launch counts are imposed as exogenous reference data, the validation exercise focuses on the model's ability to reproduce the historical evolution of three stock variables: the number of spacecraft in orbit, the debris stock, and the total number of tracked objects in Earth orbit.

The historical calibration run reproduces the long-run evolution of spacecraft stock very closely and also captures the broad upward trajectories of debris stock and total tracked objects in Earth orbit. In particular, the model reproduces not only the overall direction of change but also the major level shifts observed in the historical reference series.

To reproduce the historical debris trajectory more accurately, the model incorporates two major debris-generating events: the 2007 Chinese anti-satellite (ASAT) test and the 2009 Iridium–Cosmos collision. In the calibration run, these abrupt increases were implemented using the PULSE function, which introduces discrete shocks at specified time points. This allows the model to capture the sharp

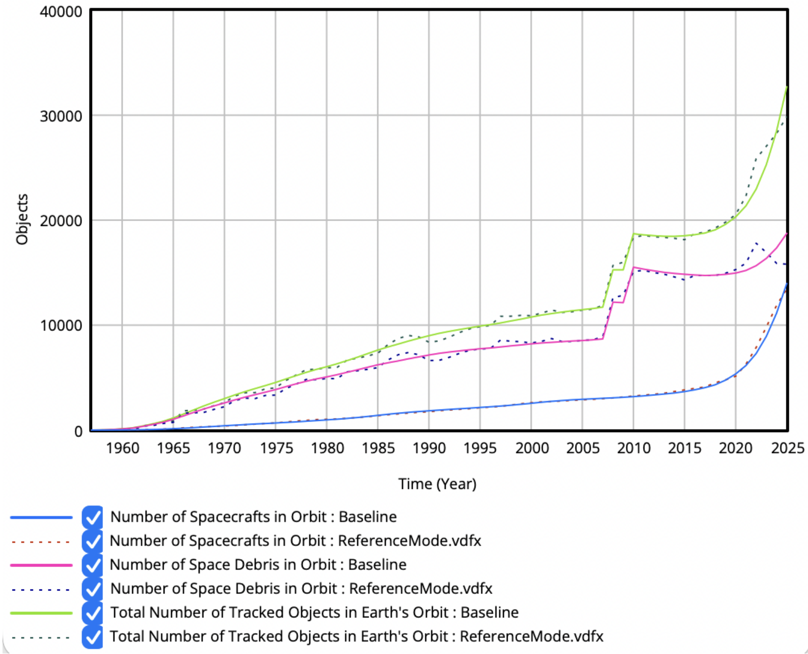


Figure 4: Behavior reproduction test for the historical period (1957–2025).

upward shifts in debris stock associated with these events.

At the same time, some short-term deviations remain, especially for debris and total objects in periods characterized by abrupt jumps in the reference data. These differences are expected, because the present model is intentionally formulated as a low-fidelity aggregate source–sink model rather than an event-level orbital-environment simulator. Accordingly, the validation criterion is not exact year-by-year matching, but the successful reproduction of long-term trends, relative magnitudes, and major turning patterns. From this perspective, the historical behavior reproduction is sufficiently strong to support the forward-looking simulation experiments conducted in the next section.

5 Results

5.1 Overview of Simulation Experiments

This section reports the simulation results for the period 2026–2075. To avoid terminological ambiguity, the 1957–2025 run presented in Section 4.2 is referred to as the historical calibration run, whereas the runs analyzed below are defined in terms of reference cases and benchmark cases.

5.1.1 Future Launch Demand Scenarios: Constant (S1), Announced-plans (S2), and High-expansion (S3)

The post-2025 experiments are organized around three alternative launch-growth scenarios. Scenario 1 is a constant-launch case in which annual successful orbital launches remain fixed at the 2025 level. This level corresponds to the 321 launches reaching orbit reported by McDowell (2026). Scenario 2 is an announced-plans case, constructed as a stylized medium-growth trajectory based on publicly known constellation deployment programs and their likely near-term implementation pressure. Its rationale draws on the continued large-scale expansion of SpaceX's Starlink system, which operated roughly 9,400 satellites in orbit by late 2025 (9,357 as of Dec. 19, 2025) (Pultarova, 2025). It also reflects U.S. regulatory authorization for an additional 7,500 second-generation satellites (Reuters, 2026; FCC, 2026), as well as other major constellation programs such as Amazon's Project Kuiper, whose initial system comprises 3,236 satellites (Roulette, 2025), and Chinese mega-constellation projects such as Qianfan ("Thousand Sails"), which have been described as targeting 15,000 satellites by 2030 (Bhattacharjee et al., 2025). Scenario 3 is a sustained high-expansion case that extends this growth pressure further and is treated as an exploratory stress case rather than as a forecast.

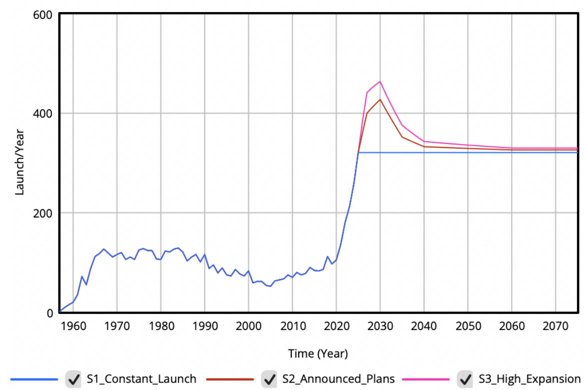


Figure 5: Future Launch Demand Scenarios

These scenarios define the scale of potential launch expansion, but do not mechanically determine the realized orbital activity. In other words, realized launch demand remains shaped by governance conditions, including the EKS-related congestion response and the launch tax–ADR (SET) policy. The aim and objective of this paper is therefore not simply to compare three growth paths, but to examine how different governance settings reshape the extent to which those growth pressures are ultimately realized. Table 2 summarizes the run configuration used in the Results section.

Table 2: Definition of simulation runs and corresponding names to graph legends.

Run name	Launch Scenario	EKS	SET Policy
R0_Historical_Calibration	Historical period (1957–2025)	Off	Off
R1_S2_NoEKS_NoSET	S2 Announced Plans	Off	Off
R2_S2_EKS_NoSET	S2 Announced Plans	On	Off
R3_S2_NoEKS_SET	S2 Announced Plans	Off	On
R4_S2_EKS_SET	S2 Announced Plans	On	On
R5_S1_EKS_NoSET	S1 Constant-Launch	On	Off
R6_S1_EKS_SET	S1 Constant-Launch	On	On
R7_S3_EKS_NoSET	S3 Sustained Expansion	On	Off
R8_S3_EKS_SET	S3 Sustained Expansion	On	On

5.1.2 Run Configuration

The analysis begins with Scenario 2, which is used as the main scenario as it represents a medium-growth future grounded in publicly announced deployment plans. Four runs are compared in order to separate EKS and SET policy effects. For ease of exposition, these runs are referred to in the text as the benchmark case (R1_S2_NoEKS_NoSET), the EKS reference case (R2_S2_EKS_NoSET), the no-

EKS policy case (R3_S2_NoEKS_SET), and the main policy case (R4_S2_EKS_SET).[8] This four-run comparison makes it possible to ask two questions in sequence: first, how much the addition of the EKS loop changes the long-run trajectory of orbital activity and debris accumulation; and second, how the launch tax–ADR regime alters those outcomes under the remediation target formulation.

The analysis then turns to the bounding cases under S1 and S3 launch scenarios. The low-growth reference case and low-growth policy case (under S1 launch scenario) correspond to R5_S1_EKS_NoSET and R6_S1_EKS_SET, respectively, while the high-growth EKS reference case and high-growth policy case (under S3 launch scenario) correspond to R7_S3_EKS_NoSET and R8_S3_EKS_SET. These runs are used to assess whether the main findings observed under Scenario 2 remain visible when launch-growth pressure is either substantially weaker or substantially stronger.

In all policy runs, the launch tax–ADR mechanism is activated from 2026 onward. Unless otherwise noted, the EKS specification uses the debris-stock proxy for perceived collision risk, and the elasticity of launch demand with respect to perceived collision risk is fixed at 0.3.[9] The present section focuses on how the model behaves under these settings.

5.2 Effects of the EKS and LT–ADR Policy under S2 Launch Scenario

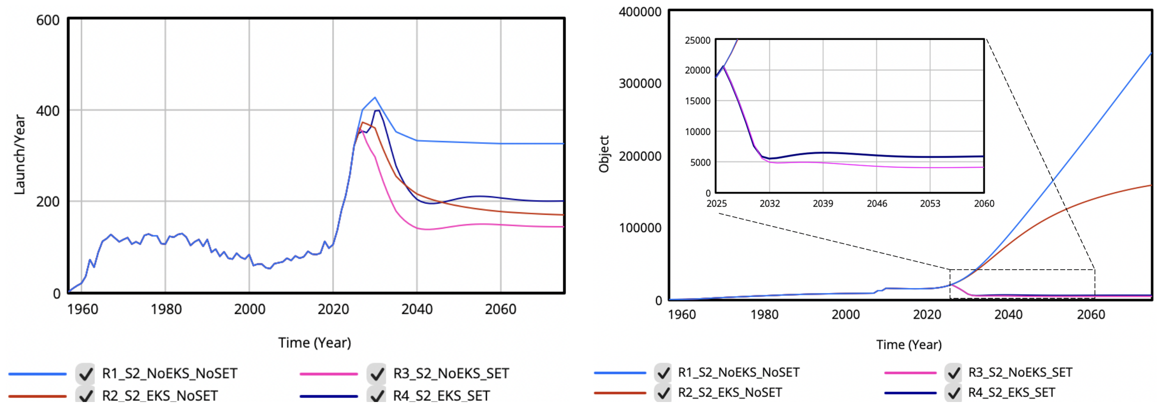
We first examine how the EKS-related balancing loop and Launch Tax–ADR (LT–ADR) policy alter the long-run trajectory of orbital activity and debris accumulation under the S2 launch demand scenario. Figure 6 compares the four core runs for Scenario 2: the benchmark case, the EKS reference case, the no-EKS policy case, and the main policy case.

Launch Demand and Debris Growth. Figure 6a shows expected launch demand. The benchmark case (R1) follows the highest long-run path, reaching a peak of 427 in 2030 and remaining at 329 in 2050 and 326 in 2075. Once the EKS loop is introduced without policy intervention, the EKS reference case (R2) peaks earlier and at a lower level, reaching 373 in 2027 and then declining to 189 in 2050 and 170 in 2075. This indicates that the EKS mechanism functions as an endogenous brake on orbital expansion under worsening congestion conditions.

The two policy cases follow a different pattern. The no-EKS policy case (R3) peaks at 362 in 2026 and then declines steadily to 146 in 2050 and 144 in 2075, yielding the lowest long-run level of expected launch demand among the four runs. By contrast, the main policy case (R4) peaks at 399 in 2031 and remains at 206 in 2050 and 200 in 2075. Thus, the main policy case sustains a higher long-run level of expected launch demand than the unmanaged EKS case (R2). This suggests that the interaction between policy intervention and congestion-driven contraction is not simply additive. Figure 6b shows the corresponding debris trajectories. The two no-policy cases continue to accumulate debris throughout the simulation period. The benchmark case rises (R1) from 158,401 in 2050 to 341,463 in 2075, while the EKS reference case (R2) remains lower but still increases from 113,772 in 2050 to 158,169 in 2075. By contrast, the two policy cases exhibit a qualitatively different outcome. The no-EKS policy case (R3) reaches 20,576 in 2026 and then declines sharply to 4,078

[8] Here, the reference cases can be interpreted as unmanaged open-access conditions, whereas the policy cases represent explicit governance through the launch tax–ADR regime.

[9] As discussed in Section 3.2.2 the model allows three alternative risk proxies to represent perceived collision risk: debris stock, total tracked objects in orbit, and debris share in orbit. Unless otherwise stated, the baseline results reported here use the debris-stock proxy. The interpretation of these assumptions is deferred to the Discussion section.



(a) Expected launch demand (b) Number of space debris in orbit

Figure 6: Comparison of four simulations under Scenario 2 (R1∼R4). See Table 2 for run definitions.

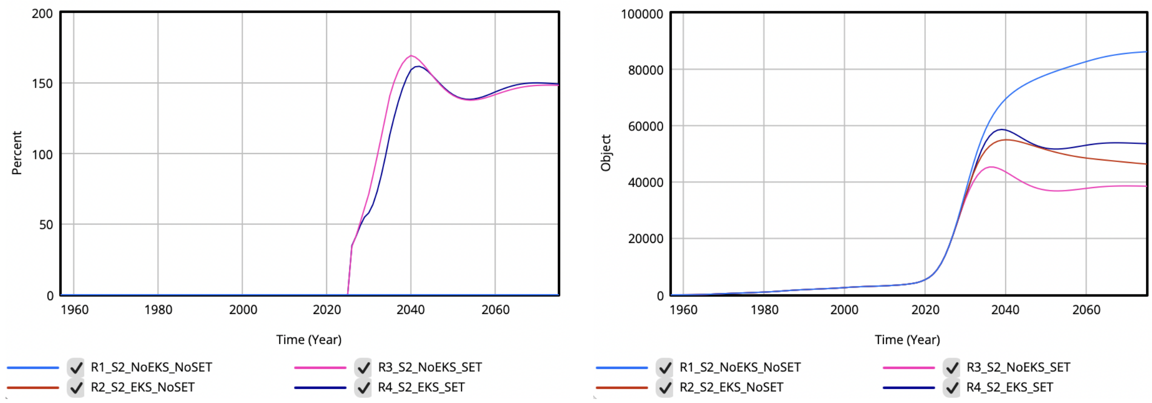
in 2050 and 4,187 in 2075. Similarly, the main policy case (R4) reaches 20,548 in 2026 and declines to 5,753 in 2050 and 5,872 in 2075. Under the current zero-debris-oriented target formulation, the policy regime therefore does not merely reduce debris at the margin; it places the system on a much lower long-term debris path.

Two results are especially important here. First, both policy cases dominate the no-policy cases in environmental terms by a wide margin. Second, the comparison between the EKS reference case (R2) and the main policy case (R4) indicates that strong debris reduction can also weaken the congestion-driven launch contraction mechanism itself. As a result, in the present simulations, the main policy case achieves a far lower debris burden than the EKS reference case, while also sustaining a higher long-run level of expected launch demand. The implications of this result for orbital utilization and fiscal burden are discussed below.

Fiscal Burden and Orbital Utilization. Figure 7a reports the required tax rate for the four runs under Scenario 2. A value of 100% means a tax equal to the average launch price. As expected, the benchmark case and the EKS reference case remain at zero throughout because no tax-based policy is activated in these runs. By contrast, both policy cases require substantial tax adjustments in the future period. In the no-EKS policy case (R3), the required tax rate peaks at 169% in 2040, then remains at 141% in 2050 and 148% in 2075.

In the main policy case (R4), the corresponding values are 162% in 2042, 142% in 2050, and 149% in 2075. Thus, the EKS-related congestion response does not mechanically reduce the fiscal burden under the policy regime. Although endogenous launch contraction helps moderate debris growth, it can also narrow the tax base, so that the required tax rate remains broadly comparable across the two policy cases and becomes slightly higher in the long term in the main policy case. For reference, these values should be interpreted as theoretical diagnostic rates implied by the current remediation target formulation rather than as directly implementable policy recommendations.

Figure 7b shows the corresponding number of spacecraft in orbit. The benchmark case produces the largest number of spacecraft, reaching 77,991 in 2050 and 86,214 in 2075, but only alongside continued debris accumulation. Among the remaining three runs, the no-EKS policy case (R3) yields



(a) Required Tax Rate

(b) Number of Spacecraft in Orbit

Figure 7: Comparison of four simulations under Scenario 2 (R1∼R4). Tax rates are expressed as percentages of the average launch price; 100% denotes a tax equal to the average launch price. See Table 2 for run definitions.

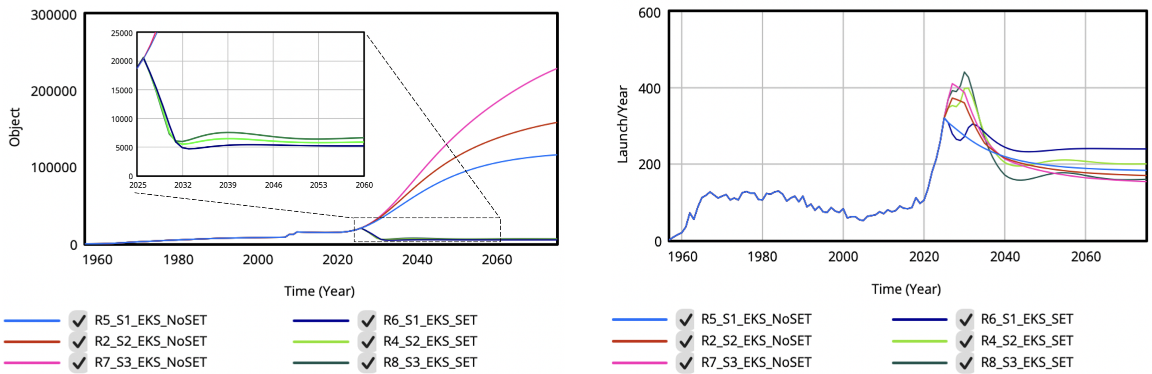
the lowest long-run utilization, with 37,116 in 2050 and 38,532 in 2075. By contrast, the main policy case reaches 52,006 in 2050 and 53,620 in 2075, exceeding the EKS reference case, which declines to 51,515 in 2050 and 46,365 in 2075.

This comparison indicates that strong debris reduction can weaken congestion-sensitive contraction sufficiently to sustain higher long-run utilization (R4) than unmanaged EKS case (R2) under the same launch-growth condition. In other words, under Scenario 2, the policy regime does not simply trade utilization for environmental improvement; it can also support a higher long-term level of orbital utilization than the unmanaged EKS case while maintaining a far lower debris burden.

5.3 Debris Growth and Launch Demand across Three Launch Scenarios

If the main pattern observed under Scenario 2 is meaningful, the next question is whether it remains visible when launch-growth pressure is either weaker or stronger. Figure 8 compares the EKS reference and policy configurations across Scenario 1, Scenario 2, and Scenario 3. The reference case comparison therefore covers the low-growth Scenario 1 reference case (R5), the Scenario 2 EKS reference case (R2), and the high-growth Scenario 3 reference case (R7), while the policy comparison covers the low-growth policy case (R6), the main policy case under Scenario 2 (R4), and the high-growth policy case (R8). All peak values reported below are identified within the 2026–2075 simulation horizon.

Debris Grwoth and Launch Demand. Figure 8a shows the number of space debris in orbit. Among the three EKS reference cases, stronger launch-growth pressure leads to a substantially higher long-run debris burden. The low-growth reference case reaches 90,363 in 2050 and 116,054 in 2075. The Scenario 2 reference case rises further to 113,772 in 2050 and 158,169 in 2075. The high-growth reference case produces the largest debris stock, reaching 142,935 in 2050 and 228,458 in 2075. In all three EKS reference cases, debris continues to increase throughout the simulation horizon, indicating that endogenous congestion effects alone do not reverse the long-run accumulation process.



(a) Number of Space Debris in Orbit (b) Expected Launch Demand

Figure 8: Debris accumulation and launch demand under three future launch scenarios (S1∼S3).

The policy cases follow a markedly different pattern. In all three scenarios, debris peaks immediately in 2026 and then declines sharply to a much lower long-run range. The low-growth policy case (R6) peaks at 20,485 in 2026 and falls to 5,207 in 2050 and 5,161 in 2075. The main policy case under Scenario 2 peaks at 20,548 in 2026 and declines to 5,753 in 2050 and 5,872 in 2075. The high-growth policy case also peaks in 2026, at 20,586, before declining to 6,398 in 2050 and 6,616 in 2075. Thus, higher launch-growth pressure still matters under the policy regime, but its effect on long-run debris remains modest relative to the much larger difference between policy and no-policy governance conditions. Even the high-growth policy case remains far below the low-growth reference case in debris terms by the end of the simulation period.

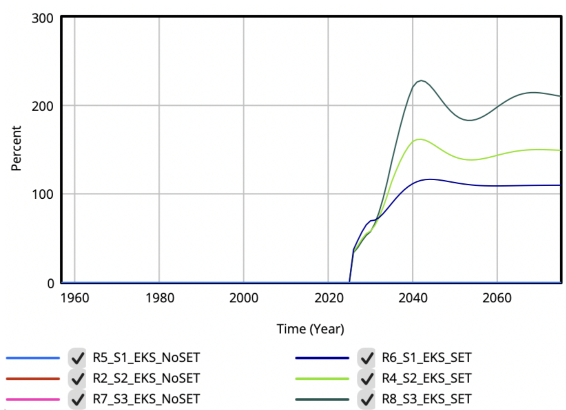
Figure 8b shows expected launch demand. Among the three reference cases, stronger launch growth pressure raises the early peak of launch demand but does not translate into a higher long-run realized level. The low-growth reference case reaches a peak of 309 in 2026 and then declines to 198 in 2050 and 184 in 2075. The Scenario 2 EKS reference case peaks higher, at 373 in 2027, but falls further to 189 in 2050 and 170 in 2075. The high-growth reference case reaches the highest early peak, 411 in 2027, yet records the lowest long-run values, declining to 181 in 2050 and 154 in 2075. This seemingly counterintuitive pattern indicates that under unmanaged EKS dynamics, stronger growth pressure can intensify congestion sufficiently to reduce long-run realized launch demand rather than sustain it.

The policy cases show a related but distinct pattern. The low-growth policy case peaks at 309 in 2026 and then stabilizes at the highest long-run level among the three policy runs, with 235 in 2050 and 240 in 2075. The main policy case under Scenario 2 peaks at 399 in 2031 and remains at 206 in 2050 and 201 in 2075. The high-growth policy case reaches the highest early peak of all policy runs, 441 in 2030, but then declines more substantially to 171 in 2050 and 160 launches per year in 2075. Accordingly, although the policy regime does not eliminate the influence of launch-growth pressure on expected demand, it changes the way that pressure is translated into long-term outcomes. Under stronger growth pressure, the system can still generate a higher short-run expansion peak, while failing to sustain a correspondingly higher long-run level of expected launch demand.

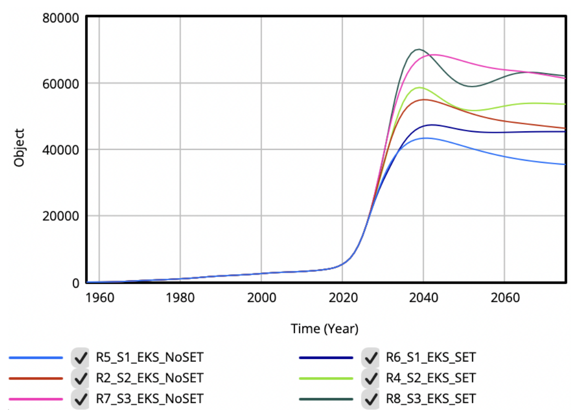
Taken together, the cross-scenario comparison points to two broader findings. First, when the governance regime is held constant, stronger launch-growth pressure worsens long-run outcomes most clearly in terms of debris accumulation. Second, the difference between governance regimes is larger than the difference between growth scenarios in determining the long-run debris trajectory. In this sense, the simulations suggest that long-run orbital outcomes are shaped not only by the magnitude of growth pressure itself, but also, and more fundamentally, by the governance regime through which that pressure is mediated.

5.4 Fiscal Burden and Orbital Utilization across Three Launch Scenarios

If policy intervention can substantially improve the long-run debris trajectory, then what fiscal burden and utilization outcome accompany that improvement under different launch-growth conditions? Figure 9 compares the policy cases across Scenario 1, Scenario 2, and Scenario 3 in terms of the required tax rate, and then contrasts the reference and policy cases across the three scenarios in terms of the number of spacecraft in orbit.



(a) Required Tax Rate



(b) Number of Spacecraft in Orbit

Figure 9: Fiscal Burden and Orbital Utilization under three launch scenarios (S1∼S3). Tax rates are expressed as percentages of the launch price; 100% denotes a tax equal to the launch price.

Figure 9a shows that stronger launch-growth pressure substantially increases the required tax rate under the policy regime.[10] The low-growth policy case (R6) reaches a peak required tax rate of 116% in 2044, and 113% in 2050 and 110% in 2075. The main policy case under Scenario 2 reaches a higher peak of 162% in 2042 and remains at 149% in 2075. The high-growth policy case produces the largest fiscal burden, peaking at 228% in 2042 and remaining at 210% in 2075. These results indicate that, under the current target formulation, the fiscal effort required to sustain a low-debris trajectory rises sharply with stronger launch expansion. In this sense, the feasibility of maintaining long-term environmental improvement depends not only on whether the policy works environmentally, but also on whether the associated fiscal burden remains governable under different growth conditions.

[10]As in the previous section, all peak values reported below are identified within the 2026–2075 simulation horizon.

Figure 9b shows the corresponding number of spacecraft in orbit. Among the three reference cases, stronger launch-growth pressure leads to a larger number of spacecraft, but only alongside the much heavier debris burden documented in Figure 8a. The low-growth reference case reaches a peak of 43,381 in 2041 and declines to 40,939 in 2050 and 35,454 in 2075. The Scenario 2 EKS reference case reaches a higher peak of 54,985 in 2040 and remains at 51,515 in 2050 and 46,365 in 2075. The high-growth reference case produces the largest utilization level among the reference runs, peaking at 68,508 in 2043 and remaining at 66,547 in 2050 and 61,400 in 2075. Thus, stronger growth pressure can still sustain a larger spacecraft in the unmanaged EKS cases, but only by tolerating a far larger long-run debris burden.

The policy cases modify this relationship in an important way. The low-growth policy case peaks at 47,369 in 2042 and remains at 45,771 in 2050 and 45,347 in 2075, staying consistently above the corresponding low-growth reference case over the long run. The main policy case under Scenario 2 peaks at 58,651 in 2039 and remains at 52,006 in 2050 and 53,620 in 2075, again exceeding the corresponding reference case (R2) in long-run utilization. The high-growth policy case reaches the highest peak overall, 70,162 in 2039, but then declines more sharply to 59,292 in 2050 before recovering to 62,175 in 2075.

As a result, under Scenario 3 the policy case remains below the corresponding reference case at mid-century, but slightly exceeds it by the end of the simulation period. This suggests that under very strong launch-growth pressure, the policy regime imposes a more pronounced medium-term restraint on orbital utilization, even though it still prevents the far larger debris accumulation observed in the no-policy case.

Taken together, these results clarify the institutional trade-off implied by the policy regime. Stronger launch-growth pressure raises both the potential scale of orbital utilization and the fiscal burden required to preserve orbital-environment improvement. At the same time, the simulations also show that substantial debris reduction does not necessarily imply lower long-run utilization than unmanaged congestion dynamics. In Scenario 1 and Scenario 2, the policy cases sustain a clearly higher number of spacecraft than their corresponding reference cases while maintaining far lower debris levels. In Scenario 3, the same pattern becomes weaker and more delayed, but it does not disappear. The broader implication is that the relationship among orbital sustainability, fiscal burden, and utilization is not mechanically fixed by growth pressure alone; it is mediated by the governance regime and by the institutional capacity to sustain that regime over time.

6 Discussion

6.1 Governance Regime Matters More than Growth Pressure

The central implication of the present analysis is that long-run orbital outcomes are shaped not only by the magnitude of launch-growth pressure, but also by the governance regime through which that pressure is managed. Stronger launch-growth pressure generally worsens long-run outcomes, especially in debris terms. Yet across all three scenarios, the difference between governance regimes is larger than the difference between growth scenarios in determining the long-run debris accumulation.

As Figure 8a depicts, in the reference cases, debris continues to accumulate throughout the simulation horizon, even when the EKS loop reduces expected launch demand. By contrast, in the policy cases, debris peaks in 2026 and declines sharply to a much lower long-run range under all three scenarios.

The key implication is therefore not simply that growth matters, but that growth pressure is mediated by institutions. In the absence of effective governance, expansion is translated into persistent debris accumulation. Under the tax–ADR regime, the same growth pressure is redirected onto a qualitatively different environmental path. From this perspective, orbital sustainability should be understood as a governance problem as much as a technological or operational one. International discussions on debris mitigation and long-term sustainability have emphasized norms, responsible behavior, and coordination mechanisms. The present results complement that perspective by showing that governance design can materially alter long-term environmental outcomes. The implication is not that the specific policy regime modeled here is immediately implementable in its present form, but that institutional design choices may matter more than growth pressure alone in determining whether orbital expansion becomes environmentally self-limiting or institutionally manageable.

6.2 Strong Debris Reduction Can Coexist with Higher Utilization

A second implication concerns the relationship between environmental sustainability and orbital utilization. The results do not support a simple one-dimensional trade-off in which stronger debris mitigation necessarily implies lower use of orbit. Instead, the simulations suggest that under some conditions, strong debris reduction can coexist with, and even support, higher orbital utilization in the long-term. This result is clearest in Scenario 2, where the main policy case achieves a much lower debris burden than the EKS reference case while maintaining a higher number of spacecraft in the long run. A similar pattern appears in Scenario 1.

The mechanism is straightforward: stronger debris reduction weakens the congestion-driven contraction generated by the voluntary launch contraction (EKS) loop. In unmanaged governance conditions, orbital activity is reduced only because worsening congestion progressively constrains future launch demand. Under the policy-based regime, environmental deterioration is moderated more directly, so that long-run utilization does not need to fall as far.

This result is not unconditional, however. Under Scenario 3, the same pattern becomes weaker and more delayed. The high-growth policy case imposes a more pronounced medium-term restraint on utilization, and its advantage over the corresponding reference case emerges only later. Thus, the simulations do not imply that environmental improvement is costless. They do, however, suggest that the relationship between sustainability and utilization is more contingent and more governance-dependent than a simple trade-off formulation would imply.

This point is relevant to current policy debates. Discussions of orbital sustainability often assume that stronger environmental controls will inevitably constrain commercial expansion, and affect the development of the market and industry (OECD, 2024). The present results suggest a more nuanced interpretation: if unmanaged congestion is itself a source of long-run utilization loss, then effective debris management may function not only as an environmental intervention but also as a condition for sustaining future orbital use.

6.3 Interpreting the Required Tax Rate and Fiscal Feasibility

The required tax rate reported in this study should be interpreted as a theoretical diagnostic rate rather than as a directly implementable policy recommendation. Its purpose is to indicate the scale of fiscal effort implied by the model's target formulation, not to propose a realistic tax level for immediate adoption. This distinction is essential because the simulated tax rates become very high, especially under stronger launch-growth scenarios.

These high values arise for several reasons. First, the policy target is intentionally stringent and oriented toward a strong reduction in long-term debris stocks rather than simply slowing the rate of its accumulation. Second, the model assumes that tax adjustment finances remediation needs without institutional buffers such as intertemporal smoothing, stabilization funds, or multi-period budgeting rules. Third, although the current specification links realized ADR to annual fundability, the funding architecture remains stylized and depends on a simplified subsidy-based cost-sharing assumption. The required tax rate is therefore useful as an indicator of how demanding the modeled objective is, but not as a literal estimate of near-term policy feasibility.

This interpretation matters because the challenge is not only environmental effectiveness, but also institutional sustainability. A regime that is environmentally effective in principle may still be difficult to sustain politically, administratively, or commercially if the associated fiscal burden becomes too large or too volatile. For this reason, the present results should be read as highlighting a policy-design problem rather than as supporting a literal tax prescription.

Several extensions could make the framework more institutionally realistic. One is target adaptation, in which the debris-management objective varies over time rather than remaining fixed in a strong stock-reduction form. Another is tax smoothing, for example through stabilization funds or moving-average adjustment rules, so that short-run fluctuations in required spending do not translate one-for-one into tax-rate changes. A third is the introduction of ADR capacity constraints and more explicit financing rules, which would distinguish more clearly between desired remediation, fundable remediation, and feasible remediation.

Together, these extensions would move the analysis from a diagnostic policy benchmark toward a more implementable institutional design framework. More broadly, the tax results clarify the role of economic instruments in orbital governance. Prior work has shown that price-based mechanisms can, in principle, improve the allocation of orbital use and internalize congestion-related externalities (Rao et al., 2020; Buchs and Bernauer, 2023; Ni et al., 2024). The present model adds a dynamic feedback perspective: fiscal burden is not only a matter of static incentive design, but also of how environmental targets, congestion effects, and the tax base interact over time.

6.4 Limitations and Future Research

Several limitations indicate directions for future research. First, the model is intentionally stylized and aggregate. It does not distinguish orbital shells in detail or fully differentiate among heterogeneous actors, spacecraft classes and debris object types, and strategic behavior across heterogeneous actors. The results should therefore be interpreted as broad dynamic tendencies rather than precise forecasts. Future work could introduce greater heterogeneity in altitude shells, actor categories, and mission types.

Second, the representation of the EKS mechanism remains simplified. The model captures endogenous demand reduction through perceived collision risk, but this channel is represented through reduced-form proxy variables rather than operator-level decision models. Future research could compare alternative proxy formulations more systematically and link the framework to richer behavioral assumptions.

Third, the policy target is deliberately stylized. The current formulation is designed to explore strong long-run stock reduction rather than to replicate any existing debris-remediation program. It should therefore not be interpreted as a literal representation of initiatives such as ESA's Zero Debris approach, which is primarily preventive and forward-looking. Alternative target formulations, including adaptive or threshold-based rules, should be examined in future work.

Fourth, both the fiscal and implementation architecture remain simplified. Although realized ADR is linked to annual fundability in the current specification, the model does not yet include mechanisms such as tax smoothing, reserve funds, or phased policy implementation that could moderate annual fiscal burden and alter the timing of remediation. In addition, the model does not yet include binding remediation capacity limits, endogenous learning effects, or differentiated removal costs across target classes such as Derelict objects and Fragments. These factors are likely to affect both the pace and the cost of debris reduction, as well as the feasibility of sustaining high fiscal burdens over time.

Finally, the present paper examines only a limited subset of robustness conditions. Future work should test the sensitivity of the main findings to alternative risk proxies, alternative elasticities of launch demand, delayed policy introduction, alternative target-adaptation rules, and more explicit funding-rule assumptions.

7 Conclusion

This paper examined how future launch-growth pressure and a tax–ADR policy interact to shape long-term orbital outcomes under the Economic Kessler Syndrome. The results indicate that environmental outcomes are determined not only by growth pressure, but also by the underlying governance regime. They also show that a strong remediation target can, under some conditions, coexist with higher long-run orbital utilization, while the fiscal burden required to sustain such improvement rises sharply with stronger launch-growth pressure. The required tax rate should therefore be interpreted as a diagnostic indicator rather than a literal policy recommendation. Importantly, the study suggests that orbital sustainability and utilization are jointly shaped by governance design, and clarifies the dynamic trade-offs and feedbacks that future institutional design must address.

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Use of Artificial Intelligence (AI)

Generative AI was used to improve the language and readability. The first author reviewed all AI-assisted text and takes full responsibility for the manuscript. All contents, results, and conclusions are the author's original work.

Notations of Model Variables and Parameters

Symbol	Description	Notes/units
L_t^{ref}	Reference (exogenous) future launch demand path.	launches/year
$\bar{L}$	Baseline future launch level (Scenario 1 constant level).	launches/year
L_t^{inc}	Incremental launches required under future scenario growth.	launches/year
D_t^{inc}	Incremental spacecraft deployment implied by scenario plans.	spacecraft/year
s_t	Average number of spacecraft per launch.	spacecraft/launch
L_t^{exp}	Expected (endogenous) launch demand after price and risk effects.	launches/year
P_t	Launch-price effect on launch demand (multiplicative factor).	dimensionless
R_t	Collision-risk effect on launch demand (multiplicative factor).	dimensionless
Q_t	Selected collision-risk proxy used to form R_t.	proxy (varies)
ε_r	Elasticity of launch demand w.r.t. perceived collision risk in $R_t = (Q_t)^{-\varepsilon_r}$.	dimensionless
A_t^{req}	Required ADR for stock-zeroization target.	objects/year
A_t^{base}	Baseline annual ADR target (fixed target used in earlier model).	objects/year
G_t	Gross debris inflow to the debris stock.	objects/year
N_t	Natural deorbiting (outflow) of debris stock.	objects/year
G_t^{L}	Launch-related debris inflow component.	objects/year
G_t^{C}	Collision-generated debris inflow component.	objects/year
A_t^{tar}	ADR target used by policy switch (either A_t^{req} or A_t^{base}).	objects/year
τ_t^{req}	Required launch-tax rate to finance the selected ADR target.	fraction of launch price
c_t^{ADR}	Average ADR cost per debris object.	dollar/object
ϕ	ADR subsidy ratio (public share of ADR cost).	fraction
p_t^{L}	Average launch price.	dollar/launch

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