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Space debris material sourcing for in-space manufacturing: a quantitative evaluation framework

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The increasing accumulation of space debris presents significant challenges to sustainable space exploration while offering opportunities for material reuse through in-space manufacturing. This research presents a framework for deriving the comprehensive value associated with using the growing space debris population as a material sourcing option for future in-space manufacturing. The growth rate of the space debris population in low Earth orbit is derived using a material flow analysis for future launch rate estimates up to the year 2050. Using these estimates, a total value calculation for space debris material sourcing is determined by considering the value associated with space debris's material market value, transportation cost reduction, and object removal risk reduction. The results of this framework indicate that cost savings from reduced material transportation to space are the most significant driver for overall space debris value, significantly outweighing the contributions of material and risk reduction value. As more data become available regarding in-space manufacturing capabilities, this framework provides insights regarding the composition of space debris value and assesses the economic viability of space debris reuse.

KEYWORDS

space debris, material reuse, in-space manufacturing, space sustainability, debris evaluation

1 Introduction

As of 2025, approximately 40,000 objects are tracked in Earth's orbit, nearly 22,500 of which are in low Earth orbit (LEO). The European Space Agency (ESA) estimates this translates to approximately 6,660,000 kg of material within 2,000 km of the Earth's surface (European Space Agency, 2025a). This population comprises both active payloads as well as space debris in the form of non-functional, artificial objects and fragments resulting from disintegration events. Over recent years, there has been an increased focus on accurately tracking the growing number of objects in Earth's orbit, specifically space debris. NASA's Debris Assessment and Software and Orbital Debris Engineering Model (ORDEM 3.2) serve as benchmarks for tracking space debris and assessing the orbital space environment (National Aeronautics and Space Administration, 2020). These models indicate the number of objects in LEO is projected to increase at a rate surpassing the frequency of new launches, primarily due to collisions and resulting fragmentation.

This phenomenon, known as the “Kessler Syndrome,” describes a point in time at which LEO will surpass its carrying capacity for space technology, resulting in collisions between objects that cause a cascade effect and exponentially increase the amount of space debris (Kessler and Cour-Palais, 1978). These findings indicate that without the implementation of effective collision avoidance capabilities and sustainable guidelines for mitigating the growth of space debris, future space operations may become increasingly challenging.

Researchers have evaluated various strategies to reduce the proliferation of space debris. One notable approach involves implementing global policy measures to ensure compliance among space organizations. Research conducted by Adilov et al. (2020) utilized an economic model to assess the impact of proposed policies—such as launch taxes and stringent decommissioning standards—on debris accumulation. Their findings indicate that, without concurrent physical debris removal methodologies, these policy measures alone are insufficient to stop long-term debris population growth.

Recognizing this limitation, attention has shifted toward active debris removal (ADR) as a necessary complement to policy interventions. Arshad et al. (2025) assessed the application of several emerging ADR technologies, which include space-based lasers, electrodynamic tethers, grappling arms, and containment systems. Space-based lasers would vaporize the surface of space debris to change its trajectory with the goal of providing a contactless manipulation of reentry paths into Earth’s atmosphere. The electrodynamic tether method would form a propulsion system using the Lorentz force generated by the interaction of an electric current with Earth’s magnetic field, allowing debris to be guided to a lower orbit for controlled deorbit. The grappling arm systems would enable spacecraft to capture and maneuver debris to a desired location, maintaining control throughout the process to reduce the risk of fragmentation or uncontrolled reentry. Containment system methods, such as deployable nets, would enclose debris for tethered transport, allowing the spacecraft to remain at a safe distance during capture and reducing the likelihood of collision.

Building on these technical assessments, recent advances achieved by Japan’s Aerospace Exploration Agency (JAXA) through the Commercial Removal of Debris Demonstrations have provided a proof of concept for capturing and deorbiting large debris using launched technologies that collected data from multiple debris objects (Yamamoto et al., 2025). This project is now progressing into Phase II, which will demonstrate a tether-based ADR method for physical debris removal in orbit by 2027. Recognizing the continued progression toward ADR implementation highlights the growing need to align technological advances with policy frameworks that support future resource reuse, such as in-space manufacturing.

The prospect of repurposing orbital waste into valuable material that supports in-space manufacturing aligns with a circular economy framework, thus advancing space sustainability (Paladini et al., 2021). Repurposing debris in this way helps establish economic incentives for debris removal, encouraging investment in the infrastructure necessary to achieve a circular economy in space. This opportunity involving the use of recycled space debris to support a circular economy in space emphasizes the importance of being able to accurately quantify the value of the current and future space debris population. One component of this involves the value of recoverable material. Leonard and Williams (2023) developed a methodology to estimate the current monetary value of debris material by calculating the material composition of space debris and multiplying that by their current market value. These findings underscore the hidden economic potential of in-orbit debris reclamation.

Another financial incentive regarding the removal of space debris arises from reducing the costs associated with launching material from Earth. Since launch costs escalate quickly, with current estimates ranging from around $4,600 to $19,900 per kilogram of payload to LEO (Center for Strategic and International Studies, 2022), sourcing materials already in space could yield substantial cost savings through fewer necessary launches.

Finally, debris removal delivers economic benefits by lowering the risk and expense associated with collision-induced space equipment replacement. Recognizing that less space debris in LEO reduces the probability of collision and damage to space technology, Vance and Mense (2013) proposed an orbital debris removal framework to estimate the value of the risk reduction associated with each piece of debris removed. This framework demonstrated that debris removal holds economic value through its inherent collision risk reduction by multiplying the expected number of collisions per year by the mean satellite replacement cost. The average cost of collisions per year was divided by the population of space debris (>10 cm in diameter) to determine the removal value per object. The findings of this research reveal a way to quantify the value of reduced risk as well as the economic feasibility of debris reclamation efforts in space.

Although research has been conducted that attempts to quantify the value associated with recycling space debris, only one category of value is evaluated at a time. Given that all components of this system contribute to its total value, a comprehensive framework is essential to capture the full economic potential of reusing space debris. This paper addresses the current gap in the literature by developing a framework that uses future debris-growth scenarios through 2050 to assess the connection between three distinct value components: material market value, launch cost reduction, and risk reduction value. By synthesizing these elements, the framework establishes a methodology that defines the relationship between key parameters needed to estimate the future value of the space debris population. The final contribution enables a general assessment of the economic feasibility of space debris reuse using data available to the user.

2 Materials and methods

The methodology for this framework begins with defining the different scenarios for future launch rates that are applied to provide a range of possible outputs for the quantified economic value of space debris. Next, the approach defines the parameters that are utilized to create the framework for each value component: material market value, transportation cost reduction, and object removal risk reduction value. The relationship between these parameters is identified within each set of equations, which allows for flexibility of data input. The approach incorporates publicly available datasets

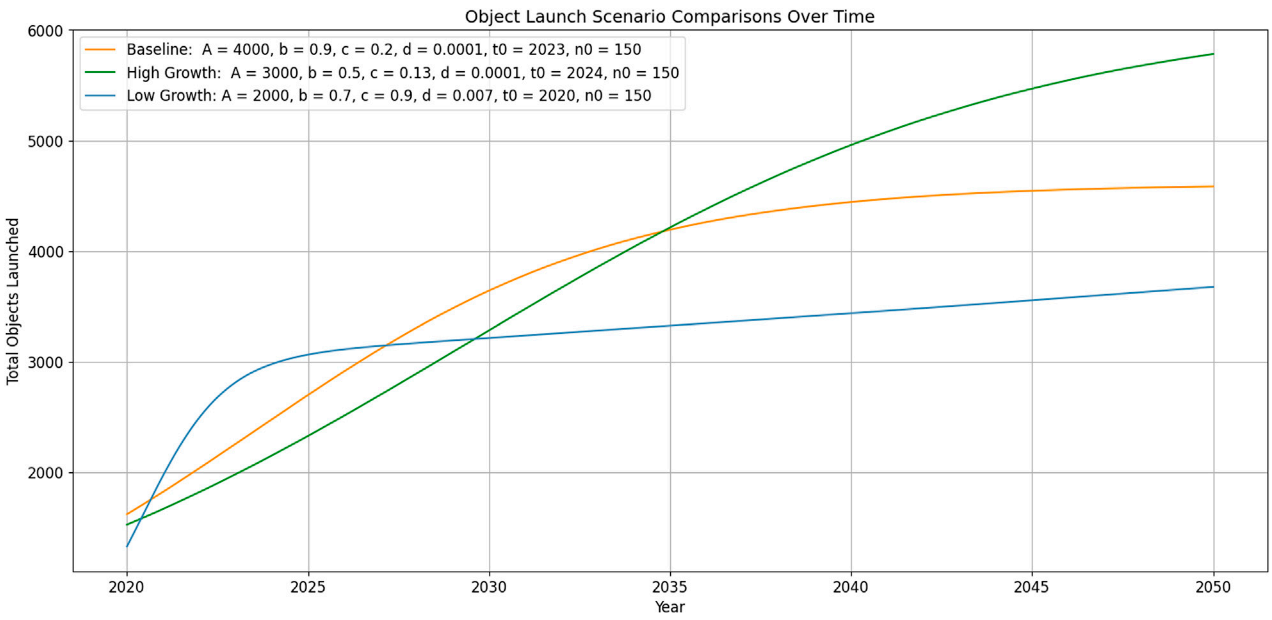

FIGURE 1
Scenario-based simulation of total objects launched annually through 2050, with variable values defined for each scenario according to Equation 1.

for debris population estimates, market pricing of materials, and launch costs. Published models are utilized to support different assumptions used within this framework. The methodology is organized into the five phases: scenario planning, material market value, transportation cost reduction, risk reduction value, and total value. This structure helps maintain traceability between the inputs, assumptions, and outputs utilized in this framework.

2.1 Scenario planning

To calculate the value of space debris in LEO up to the year 2050, data on yearly space debris aggregates are needed. These data values can be estimated from annual launch rates of all categories of space missions. Due to the uncertainty regarding these future estimates, three launch rate simulation scenario equations created by Wilson et al. (2024) are depicted in Figure 1, providing a baseline as well as an upper and lower bound for follow-on calculations.

The following definitions contextualize the conditions that could reasonably produce each of the three future launch rate scenarios. The Baseline scenario assumes a gradual expansion of the space industry driven by commercial and government activity, followed by a period of stalled growth due to competitive market pressures and enforced space sustainability standards. The High Growth scenario assumes a gradual expansion of the space industry driven by commercial and government activity that extends beyond the year 2050 and is indicative of a future where rapid space development is prioritized over space sustainability. The Low Growth scenario assumes a brief continuation of the explosive expansion in the space industry that has been occurring over the last few years, followed by a period of reduced growth. This scenario's assumed reduction in future growth could be the result of the implementation of strict space sustainability policies, such as enforced compliance with international standards or launch taxes.

2.1.1 Material flow analysis

Deriving the accumulation of space debris in LEO from predicted launch rates is essential for estimating the potential material sourcing value of the total debris mass. A material flow analysis is used to determine the proportion of launched technology that will contribute to the space debris population at the end of its operational life.

In this system, the inflows are all objects launched into space annually (N_{launch}), which are simulated using Equation 1 and correspond to the scenarios identified in Section 2.1 (Wilson et al., 2024). The outflows include primary mechanisms through which launched space technology exits the LEO environment, which are assumed to be comprehensively covered through the categories of decommissioning, launch failure, and space missions extending beyond LEO. For outflow calculations, data preceding 2015 were excluded due to lower annual launch rates, which introduce greater variability and potentially skew results.

$$N_{launch}(t) = n_0 + \frac{A \times \exp(d(t - t_o))}{(b + \exp(-c(t - t_o)))} \quad (1)$$

Data from the Aerospace Corporation's Aerospace Corporation, 2025 and research conducted by Pardini and Anselmo (2025) were used to estimate the percentage of launched technology that is decommissioned via removal from LEO and subsequent reentry into Earth's atmosphere. The average percentage of launched technology decommissioned annually (DC) over the last 10 years was calculated to be approximately 14.8%.

To estimate the percentage of launches that fail to achieve orbit, the average launch failure rate (LF) over the past 10 years was

TABLE 1 10-year averages for the outflow categories in the material flow analysis.

Year	Decommission	Launch failure	Beyond LEO
2024	17.5	3.0	25.7
2023	22.6	6.0	45.6
2022	7.9	4.0	20.2
2021	8.2	9.0	10.4
2020	7.2	12.0	26.1
2019	12.8	7.0	37.5
2018	17.3	4.0	29.7
2017	9.0	9.0	36.6
2016	21.7	5.0	10.8
2015	23.4	7.0	24.1
Average	14.8	6.6	26.7

calculated, yielding an average of 6.6% (Todd, 2025; McDowell, 2023). This failure rate specifically accounts for launches that did not exit Earth's atmosphere and, therefore, do not contribute to the space debris population.

Using orbital data from the European Space Agency's Space Environmental Reports and the United States Space Force's Orbital Box Score, the 10-year average rate of objects launched to orbits beyond LEO (*BL*) was 26.7% (European Space Agency, 2025b; United States Space Force, 2025). This percentage accounts for space technology operating in orbital regimes beyond LEO, such as Medium Earth Orbit, Geostationary Orbit, Highly Eccentric Earth Orbit, High Altitude Earth Orbit, and Escape Orbits, and therefore does not contribute to the space debris population in LEO. The 10-year outflow averages for the system are further defined in Table 1.

The Sankey diagram in Figure 2 provides a visual representation of the material flow analysis for this system. The diagram depicts a singular inflow for objects entering the system, with each flow indicating the percentage of the initial inflow it comprises. The difference between the inflow and outflow rates represents the material in LEO. This material is categorized as either operational technology or space debris. It is assumed that operational technology that does not exit the system via an outflow ultimately becomes space debris. As a result, Equation 2 calculates the proportion of space debris (P_{SD}) by subtracting the outflow proportions (*DC, LF, BL*) from the initial inflow (F_{in}). These proportions are applied to the object launch rates for each scenario to determine the annual number of objects that will contribute to the populations of space debris, beyond LEO missions, launch failures, or decommissioned objects, as depicted in Figure 3.

$$\begin{aligned} P_{SD} &= F_{in} - DC - LF - BL \\ P_{SD} &= 1.0 - 0.066 - 0.267 - 0.148 = 0.519 \end{aligned} \quad (2)$$

2.1.2 Deriving mass of space debris

To estimate the annual mass of space debris for each scenario, object counts from each category were converted into mass estimates using data from the European Space Agency's Database of Information System Characterizing Objects in Space (DISCOSweb) and the United States Space Force's Orbital Box Score (European Space Agency, 2025b; United States Space Force, 2025). These data points reveal that of the approximately 9,200 space debris objects currently being tracked in Earth's lower atmosphere, 52.2% are classified as payloads (objects fulfilling mission-related functions), 7.9% are classified as mission-related objects (objects released intentionally to support payload function), and 39.9% are classified as rocket bodies (components of launch vehicles released while transporting payloads).

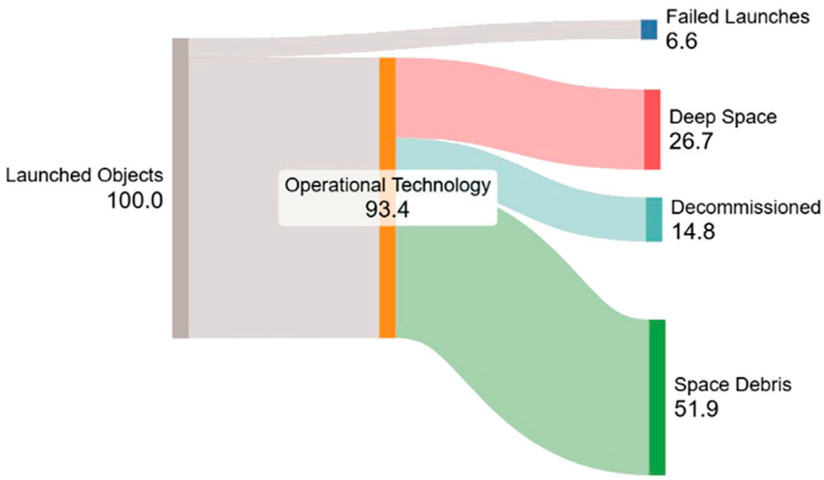

FIGURE 2
Sankey diagram displaying the percentage of launched objects that become outflows or space debris in Earth's orbital system.

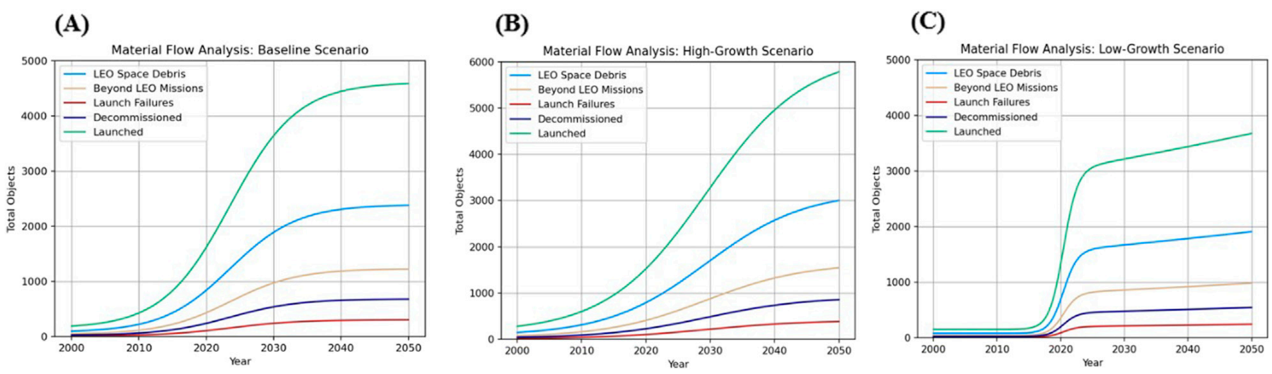

FIGURE 3
Classification of the number of objects that make up the flow of material each year based on the simulated launch rate scenarios; **(A)** Baseline, **(B)** High Growth, **(C)** Low Growth.

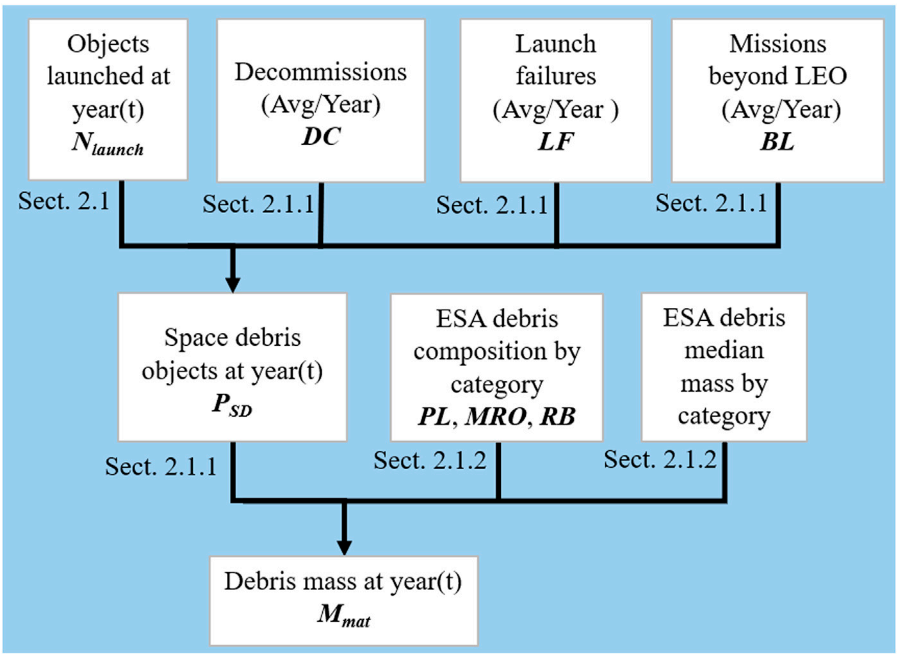

FIGURE 4
Scenario planning framework flowchart illustrating the relationship of variables used in the calculations.

Research conducted by Leonard and Williams (2023) used DISCOSweb data to identify the minimum, median, and maximum estimates for both mass and object count within each category of space debris. Given the wide range of possible mass values in each debris category, subsequent calculations relied on the median estimates, as these better represent the central tendency of the data. Following their methodology, the estimated mass per object in each category was determined by dividing the median mass by the number of objects: approximately 830 kg per payload (PL), 63 kg per mission-related object (MRO), and 1,570 kg per rocket body (RB). As shown in Equation 3, these values were used to estimate annual material mass (M_{mat}) by applying each category's proportional share, multiplying it by the corresponding median mass, and adjusting for the proportion of debris among all objects launched annually. Figure 4 defines this relationship between variables by illustrating the framework for calculating the mass of space debris for each year and scenario.

$$M_{mat}(t) = N_{launch}(t)^{*}(P_{SD})^{*}((0.522^{*}PL) + (0.079^{*}MRO) + (0.399^{*}RB)) \quad (3)$$

TABLE 2 Space technology material composition percentages and market value.

Material class	% composition within space technology	Composition within material class	Material value 2024 -2050 ($/kg)	Lower-bound scenario ($/kg)	Upper-bound scenario ($/kg)
Metallic materials	70	Aluminum (30%)	2.44	2.23	2.65
		Steel (5%)	0.42	0.34	0.50
		Copper (10%)	10.20	2.60	17.80
		Aluminum alloy (30%)	3.30	2.23	4.37
		Silver (5%)	1,029.40	226.00	1832.80
		Nickel (5%)	15.60	9.27	21.93
		Titanium alloy (15%)	45.00	27.80	62.20
		Sum value	61.76	17.55	105.98
Polymerics, composites, ceramics	30	Sum value	15.45	6.95	26.51

2.2 Material market value

2.2.1 Average material composition and value of space technology

After determining the mass of space debris material for each simulated year of future launches, the total material value was calculated. These masses were translated into monetary values by analyzing the material composition of space technology components. Drawing upon the research by Leonard and Williams (2023), which provides insights into the material composition per kilogram of space technology, the materials were categorized into four primary groups: metallics, polymerics, composites, and ceramics. Their study estimates that approximately 70% of space technology mass comprises metallics, while the remaining 30% consists of the other three categories.

Additionally, the metallic material class was further broken down into its constituent metals. The material composition percentages identified in Table 2 were multiplied by the corresponding baseline value of each material per kilogram as found in the United States Geological Survey's 2025 Mineral Commodity Summary (United States Geological Survey, 2025). For the baseline material value used in this framework, it is assumed that the present value of the material remains constant from 2024 to 2050. This assumption derives from the idea that the effects of inflation and discounting approximately offset one another over the long term. In other words, if future material values were adjusted upward using an inflation rate and then discounted back to present value using a similar interest rate, the net effect would be minimal. As a result, using a constant present value avoids introducing unnecessary complexity to this process without significantly impacting the accuracy of the results.

To test the impact of this material value assumption, the upper and lower bound scenario values presented in Table 2—representing potential variations in future market conditions and material scarcity—will be evaluated in the sensitivity analysis. The lower bound scenario uses the lowest inflation-adjusted prices for each material dating back to 2000 (expressed in 2025 United States dollars). The upper bound scenario adds the difference between the lower bound and current 2025 prices to estimate the potential highest price levels that could be reached over the next 25 years (United States Geological Survey, 2025).

For each launch rate scenario, the projected annual mass of launched objects is multiplied by the 2025 value per kilogram of metallics, polymerics, composites, and ceramics, accounting for their respective proportions of the total composition. To account for the material value of space debris launched into space before 2024, the scrap material valuation of $97 million from Leonard and Williams (2023) is utilized. By incorporating this historical material value into the annual projections, we calculate the total estimated value of the space debris material population for each scenario by 2050.

2.2.2 Degradation rate of materials

Research conducted by Samwel (2014) evaluates degradation rates for varying materials exposed to atomic oxygen conditions in LEO. This research specifically identifies erosion rates for materials in a simulated LEO environment for a mission length of 1 year, reporting yields in units of 10^{-24} cm^3 per atom. These values are then converted into material degradation percentages per kilogram. The specific results for each material are identified in Table 3; the average of polymer materials tested in Samwel's research is used to represent the degradation rate for the non-metallic material class. The asterisks denote metals not included in Samwel's report; therefore, a degradation rate of 0.0 is assumed.

Wakai et al. (2021) conducted an experimental assessment to calculate the degradation rate of five stainless-steel and aluminum compositions exposed to constant radiation in a thermal reactor for approximately 3 months (84 days). This study found that radiation-simulated aging primarily resulted in reduced ductility and material strength, with minimal structural changes observed after the first 2 months (60 days). The reduction of area percentage determined in this study is used as an approximate degradation rate in terms of the loss of effective mass-bearing capacity per kilogram of space debris material. For material included in the framework but not tested in this study, the average of these mass loss percentages is used.

TABLE 3 Space technology material degradation rates.

Material class	Composition within material class	Atomic oxygen degradation percentage (decimal)	Radiation degradation percentage (decimal)	Thermal cycling degradation percentage (decimal)	Ultraviolet light degradation percentage (decimal)
Metallic materials	Aluminum (30%)	0.0	0.257	0.067	0.0041
	Steel (5%)	0.0*	0.364	0.067	0.021
	Copper (10%)	0.00054	0.298	0.067	0.0058
	Aluminum alloy (30%)	0.0	0.274	0.067	0.0041
	Silver (5%)	0.612	0.298	0.067	0.01
	Nickel (5%)	0.0*	0.298	0.067	0.01
	Titanium alloy (15%)	0.00033	0.298	0.067	0.01
Polymerics, composites, ceramics		0.148	0.298	0.067	0.01

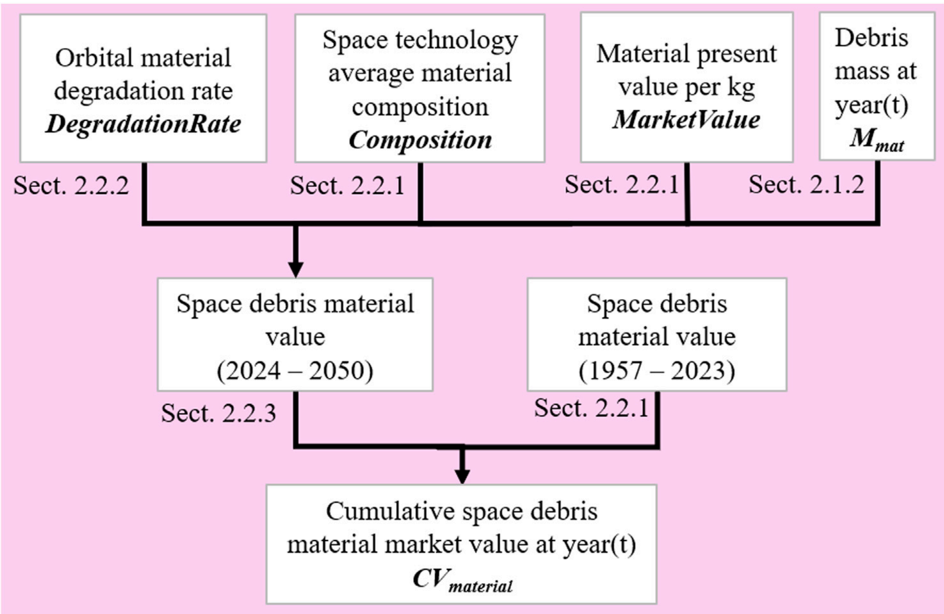

FIGURE 5
Material market value framework flowchart illustrating the relationship of variables used in the calculations.

Research conducted by Elmaryami et al. (2020) examines the corrosion rate of carbon steel subjected to residual structural stresses due to repeated temperature changes from thermal cycling. This study found that the average loss of carbon steel weight was approximately 6.7% and reached a steady state after 30 thermal cycles. Assuming at least 30 thermal cycles occur during the time frame of applying this framework, the percentage of relative weight loss determined in this study is used as an approximate degradation rate for each kilogram of the included space debris materials.

Burleigh et al. (2003) conducted a study to estimate the effects of ultraviolet light exposure on the degradation rate of different materials. This study found that the tested metals, aluminum, copper, and carbon steel, reached approximate steady state mass losses of 0.41%, 0.58%, and 2.1%, respectively, after 5 months of constant ultraviolet light exposure. For material included in the framework but not tested in this study, the average of these mass loss percentages is used. The relative weight loss determined in this research is applied as an approximate degradation rate per kilogram of space debris material.

The derived degradation rates are applied across all materials included in the framework and are depicted in Table 3. These rates provide a reasonable estimate of the proportion of the space debris population that may not be suitable for material sourcing due to environmental degradation. The ranges of values are also

TABLE 4 Proportion of space missions categorized into each launch vehicle class within the specified timeframe and the associated cost per kilogram of payload.

Class	1957–2019		2010–2019		Average $/kg
	Count	Proportion	Count	Proportion	
Heavy	23	0.377	3	0.200	4,633.00
Medium	29	0.475	4	0.267	7,950.00
Small	9	0.148	8	0.533	19,900.00

incorporated into the sensitivity analysis to evaluate the impact of their variability.

2.2.3 Material market value framework

The material market value framework estimates the value of the material contained within the space debris population in LEO. To quantify this value, the average value per material class is determined for 1 kg of space debris. To calculate the material unit value per kg of space debris ($UnitValue$), each material's market value ($MarketValue$) (Section 2.2.1) is multiplied by its composition within the material class and overall technology ($Composition$) (Section 2.2.1). Next, the annual space degradation rates for the different materials ($DegradationRate$) (Section 2.2.2) are applied to each respective material in Equations 4, 5 to account for the reduced value of debris that is no longer viable for future in-space manufacturing. These values are added together starting in the year 2024 to show the predicted cumulative material value growth of space debris over time. Finally, the material value from debris launched before 2024 (Section 2.2.1) is added to account for the material already present in orbit.

This framework, shown visually in Figure 5 and expressed mathematically in Equation 6, outlines how the cumulative material market value ($CV_{material}$) is calculated for each year and scenario.

$$UnitValue_{metal} = \sum_i \left(Composition_{i,metal} {}^* MarketValue_i {}^* \left(1 - DegradationRate_i\right)\right) \tag{4}$$

$$UnitValue_{non} = \sum_j \left(Composition_{j,non} {}^* MarketValue_j {}^* \left(1 - DegradationRate_j\right)\right) \tag{5}$$

$$CV_{material}(t) = \$97,000,000 + \sum_{t=1}^{25} \left(M_{mat}(t) {}^* \left(UnitValue_{metal} + UnitValue_{non}\right)\right) \tag{6}$$

2.3 Transportation cost reduction value

2.3.1 Launch vehicle class proportions

The Center for Strategic and International Studies (CSIS) May (2021) reports inflation-adjusted launch costs to LEO for each vehicle class as determined by payload mass: small (<2,000 kg), medium (2,000–20,000 kg), and heavy (>20,000 kg).

Given the significant differences in payload cost per kilogram across launch vehicle classes, the frequency distribution of vehicles within each class was identified. Historical data (1957–2019) shows class frequency distributions of 37.7% small, 47.5% medium, and 14.8% heavy. However, recent trends (2010–2019) shift this to 53.3% small, 26.7% medium, and 20.0% heavy, which is used to provide an approximate launch vehicle class distribution through 2050, as shown in Table 4.

2.3.2 Launch vehicle class costs

In addition to providing data regarding the payload capacity of launch vehicles, the CSIS May (2021) specifies inflation-adjusted costs per kilogram for launching payloads to LEO, grouped by vehicle class. To estimate current launch costs by vehicle class, the average payload cost per kilogram for each class was calculated using data from 2010 to 2019 in Table 4. Data before 2010 is excluded from this calculation to reduce skew introduced by historically higher launch costs, which do not reflect current trends in cost due to technological advancements.

These class-specific costs and launch vehicle proportions are used to estimate the transportation cost of the material present in space debris ($C_{MatTranspo}$). For the period 1957–2023, the estimated debris mass of 6,978,000 kg (Leonard and Williams, 2023) is multiplied by the historical distribution of launch vehicle frequency ($Dist$) (1957–2019) and their corresponding payload cost per kilogram ($PLCost$), as expressed in Equation 7. This process is repeated in Equation 8 for the years 2024–2050, but the projected space debris mass (Section 2.1.2) is multiplied by the proportion of launch vehicle mission classes from 2010 to 2019 to more accurately represent recent trends in launches. This method ensures both historical and future estimates are based on launch data that accurately reflects their respective contexts.

$$C_{MatTranspo}(1957 \le t \le 2023) = M_{mat}(t) {}^* \left(Dist_{Heavy} {}^* PLCost_{Heavy} + Dist_{Med} {}^* PLCost_{Med} + Dist_{Small} {}^* PLCost_{Small}\right)$$

$$C_{MatTranspo}(1957 \le t \le 2023) = 6,978,000\, kg {}^* \left(0.377 {}^* 4633 \frac{\$}{kg} + 0.475 {}^* 7950 \frac{\$}{kg} + 0.148 {}^* 19900 \frac{\$}{kg}\right) = \$59,091,200,000 \tag{7}$$

$$C_{MatTranspo}(2024 \le t \le 2050) = M_{mat}(t) {}^* \left(Dist_{Heavy} {}^* PLCost_{Heavy} + Dist_{Med} {}^* PLCost_{Med} + Dist_{Small} {}^* PLCost_{Small}\right)$$

$$C_{MatTranspo}(2024 \le t \le 2050) = M_{mat}(t) {}^* \left(0.2 {}^* 4633 \frac{\$}{kg} + 0.267 {}^* 7950 \frac{\$}{kg} + 0.533 {}^* 19900 \frac{\$}{kg}\right) \tag{8}$$

2.3.3 Annual launch cost reduction

According to Adilov et al. (2024), inflation-adjusted launch costs have declined significantly since 2000, approximately 7.5% annually for commercial launches and 3.6% annually for non-commercial launches. Their regression analysis determined a 4.4% average rate of decrease per year for launches to LEO, with a 95% confidence interval ranging from 2.8% to 6.1%. Breakthroughs in technology, the development of lighter payloads, and the commercialization of the space industry drive this reduction in launch costs. The 4.4% predicted reduction in annual cost is used in subsequent calculations to adjust future estimates of payload transport costs to LEO.

2.3.4 Number of operational ADR systems

Research conducted by May (2021) through Aerospace's Center of Space Policy and Strategy (CSPS) suggests that the United States, China, Japan, Russia, and the United Kingdom are global leaders in ADR development. The study further identifies ten ADR systems currently recognized by these countries as being in advanced stages of research, development, or demonstration. Given their prominence in space exploration and advancements in ADR research, this framework assumes that these nations are likely to operate multiple iterations of the identified systems for a combined total of approximately 50 operational ADR systems in the coming years. This number remains uniform throughout the analysis, implying an assumption of a replacement scenario rather than growth. Since there exists limited data that attempts to project the number of operational ADR systems in future years, the estimated number of ADR systems used in this framework is a key parameter that will be examined further in the sensitivity analysis across the following scenarios. Specifically, a lower bound scenario assumes minimal ADR technology development (uniform deployment of 30 ADR systems annually) and an annual failure rate three times higher than the current launch failure rate identified in Section 2.1.1 (19.8%). Conversely, the upper-bound scenario assumes an accelerated rate of ADR technological development (three additional ADR systems added annually starting in 2030) and an annual failure rate consistent with the current launch failure rate identified in Section 2.1.1 (6.6%). Testing these scenarios in the sensitivity analysis enables a more comprehensive assessment of how variations in ADR growth, reliability, and technological progress could influence the outcome of the framework.

2.3.5 Annual costs of ADR systems

An important factor in considering space debris as a material sourcing option for in-space manufacturing is the retrieval process. Although ADR technology is rapidly advancing, it is worth noting that these added benefits do not come without costs associated with research, development, launch, maintenance, and operation. For this framework, it is assumed that ADR systems have already been developed and are actively deployed in LEO. As a result, research and development costs are not included in this framework, whereas recurring, annual costs of ADR system launches, operations, and maintenance are considered. This approach simplifies the model while capturing the main ongoing expenditures associated with ADR deployment.

Braun et al. (2014) estimated operations and maintenance (O&M) costs for ADR systems using a model that incorporated personnel, service, infrastructure, subsystem reliability, and mission duration. The result of this analysis was an O&M cost of approximately $4.6 million for every 3 months per operational ADR system. Adjusting for inflation from 2014 to 2025 and converting to an annual figure yields an estimated cost of $24,855,964.40 per ADR system per year. Equation 9 revealed that O&M costs total approximately $1.24 billion annually for 50 systems.

Due to the wide range of ADR designs and associated masses, this framework adopts the average payload mass estimated by Braun et al. (2014)—2,270 kg—as a representative value. This places ADR systems within the medium payload launch vehicle class, corresponding to the launch cost of $7,950 per kilogram (Section 2.3.2; Table 4). While ADR mission durations vary, current prototypes are designed for an average operational life of roughly 5 years (May 2021). Therefore, in Equation 10, it is assumed that each system incurs one launch cost every 5 years to replace the expiring system.

The estimated number of operational ADR systems, along with annual operations, maintenance, and launch cost data, is used in Equation 11 to calculate the total estimated yearly cost (*TotalADRCost*) of utilizing ADR systems to retrieve space debris in LEO.

$$\begin{aligned} \textit{Annual ADR Sytem O\&M Cost} &= \$24,856,000 * 50 \\ &= \$1,242,800,000 \end{aligned} \tag{9}$$

$$\begin{aligned} \textit{Annual ADR System Launch Cost} &= \$7,950 * 2270 * \frac{1}{5} * 50 \\ &= \$180,500,000 \end{aligned} \tag{10}$$

$$\begin{aligned} \textit{Total ADR Cost} &= \$1,242,800,000 + \$180,500,000 \\ &= \$1,423,300,000 \end{aligned} \tag{11}$$

2.3.6 Transportation cost reduction value framework

The transportation cost reduction value framework estimates the monetary savings that could be achieved by using existing space debris for in-space manufacturing rather than launching equivalent material from Earth. To quantify this value, the projected material transportation cost for each year from 2024 to 2050 (Section 2.3.2) is adjusted by the annual launch cost reduction rate of 4.4% (*LaunchCostRed*) (Section 2.3.3) to account for the expected improvement in launch efficiency over time. This adjustment captures the value of avoided launch expenses.

The annual cost of operating ADR systems (Section 2.3.4) is subtracted from this cost reduction value, as these expenditures offset some of the benefits gained from reduced launch needs. Finally, the transportation value of the existing space debris population from 1957 to 2023 (Section 2.3.2) is added. This historical component remains constant across all scenarios since it is based on known data rather than future projections.

This framework, shown visually in Figure 6 and expressed mathematically in Equation 12, outlines how the transportation cost reduction value ($CV_{transpo}$) is calculated for each year and scenario.

$$\begin{aligned} CV_{transpo}(t) = {} & C_{MatTranspo}(1957 \le t \le 2023) \\ & + \sum_{t=1}^{25}\Big(\big(C_{MatTranspo}\ (2024 \le t \le 2050) * \\ & (1 - LaunchCostRed)^{t}\big) - TotalADRCost\Big) \end{aligned} \tag{12}$$

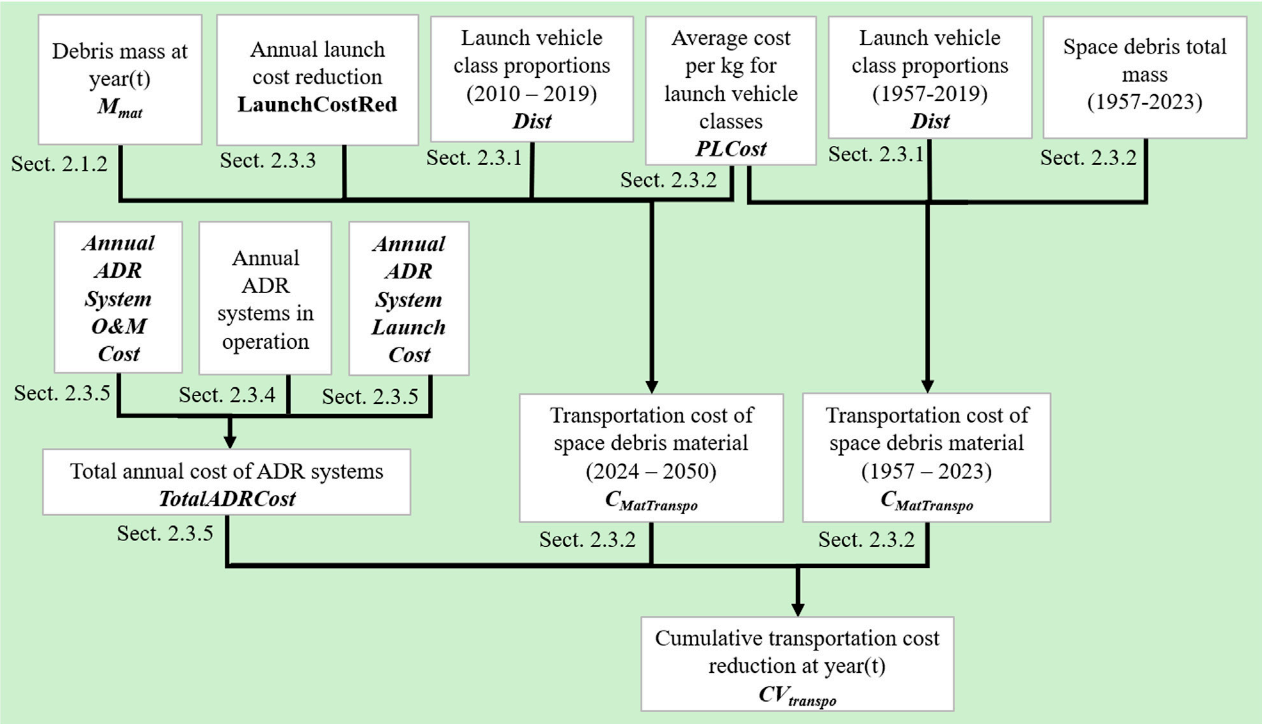

FIGURE 6
Transportation cost reduction framework flowchart illustrating the relationship of variables used in the calculations.

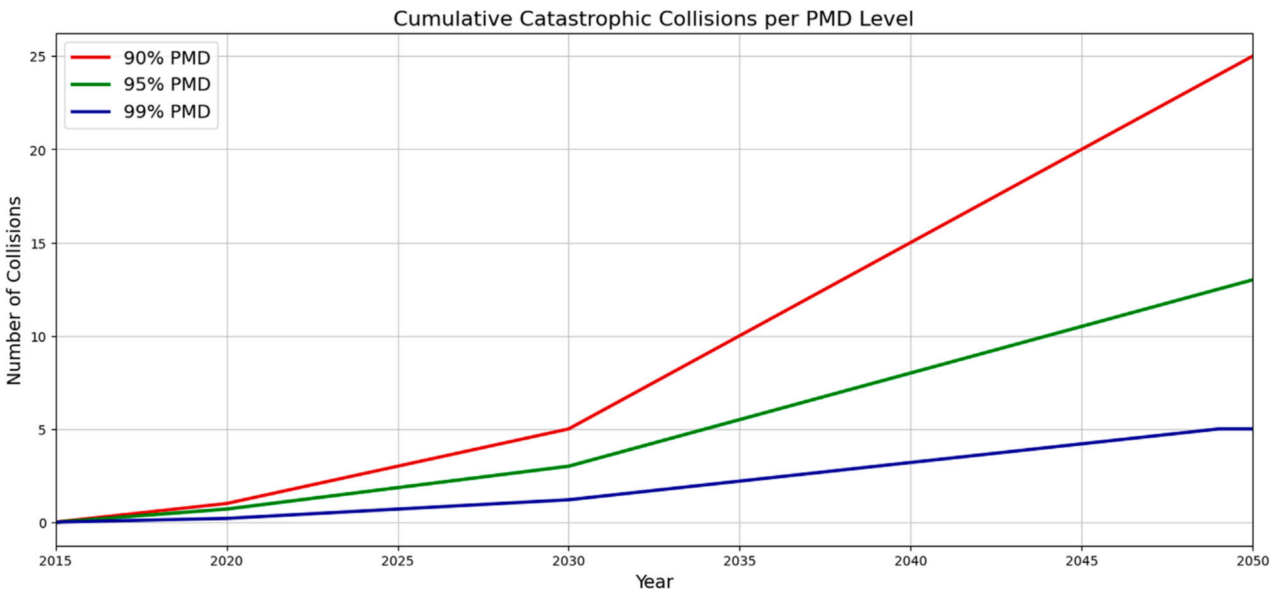

FIGURE 7
Predicted number of cumulative catastrophic collisions each year in LEO based on PMD rates (Liou et al., 2018).

2.4 Object removal risk reduction value

2.4.1 Predicted annual catastrophic collisions

As identified by the Kessler Syndrome prediction, the increased likelihood of collisions represents the most significant risk that space debris poses to active space technology. While some collisions may inflict minimal to no damage, catastrophic impacts can lead to the complete fragmentation of the affected spacecraft and the generation of substantial additional debris (Liou et al., 2018). In a NASA study

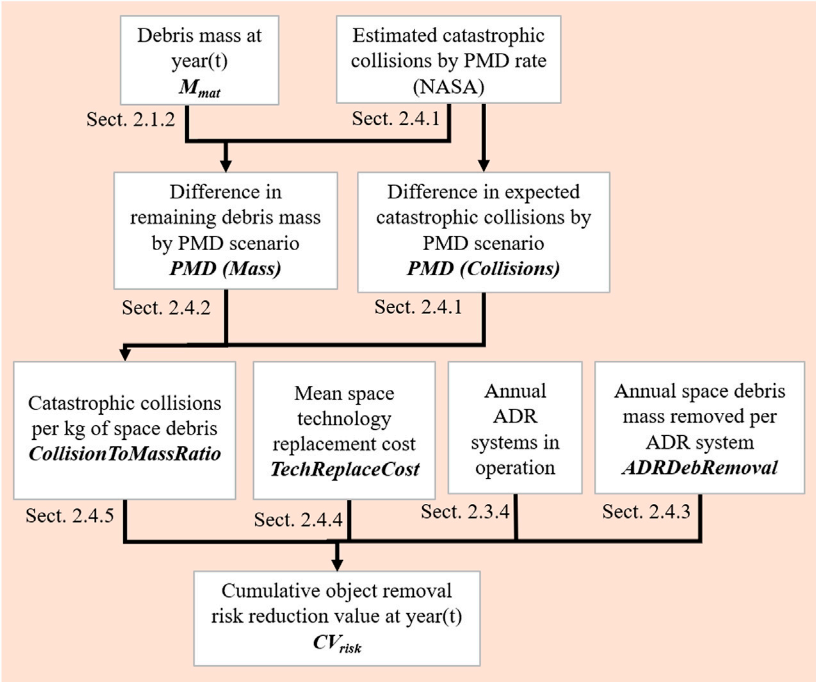

FIGURE 8
Object removal risk reduction value framework flowchart illustrating the relationship of variables used in the calculations.

assessing the impact of space debris in LEO, Liou et al. (2018) employed a Monte Carlo simulation to estimate the long-term cumulative number of catastrophic collisions under varying levels of post-mission disposal (PMD) compliance for decommissioned space technology. The study assumed that achieving 90%, 95%, and 99% PMD compliance would involve executing orbital maneuvers intended to meet the Federal Communications Commission's (FCC) mandatory 5-year post-mission disposal requirement, with effectiveness corresponding to the specified compliance level. For this framework, only the estimated number of catastrophic collisions projected through the year 2050 is considered, as seen in Figure 7.

2.4.2 Space debris populations after PMD

The PMD process is used to maneuver space technology out of its original operational orbit and into a lower altitude region of space, where it poses a reduced risk of collision with other objects during the deorbiting phase. A PMD compliance level of 90% indicates that 90% of launched space assets are successfully removed from operational orbit at the end of their active life within the 5-year requirement mandated by the FCC. This means that 10% of space technology launched annually remains in orbit as space debris. By understanding this process, Equation 13 can be applied to estimate how different PMD compliance levels affect the future space debris population under each growth scenario.

$$Space\ Population\ at\ X\%\ PMD\ (t) = M_{mat}\ (t)^{*}\ (1 - 0.X) \qquad (13)$$

2.4.3 Annual debris removal rate of ADR systems

To estimate the annual debris removal capability of ADR systems, Barbee et al. (2012) calculated the required thruster-specific impulses based on the number of targeted debris objects and the corresponding launch mass of ADR technology. The analysis suggested that, given the propulsion technology available at the time, ADR systems could feasibly remove 3 to 5 pieces of large orbital debris per year.

Building on these findings, McKnight et al. (2021) identified the 50 most statistically concerning debris objects in LEO to help ADR missions prioritize targets with the highest risk of causing significant damage. The average mass of these high-priority objects is 5,295 kg. Assuming each ADR system removes an equivalent mass of three high-priority debris objects annually, this corresponds to approximately 15,880 kg of debris removed per system per year. With 50 ADR systems in operation annually, as described in Section 2.3.4, the total estimated mass of debris removed from LEO each year is approximately 794,220 kg.

2.4.4 Space technology replacement cost

Given the range of space missions, the replacement cost resulting from a catastrophic collision can vary significantly. The estimated replacement costs for various mission types in LEO are based on NASA's cost–benefit analysis of orbital debris remediation (Colvin et al., 2023). Since most of the space technology in LEO consists of satellites, there is a greater weight assigned to satellite replacement costs when

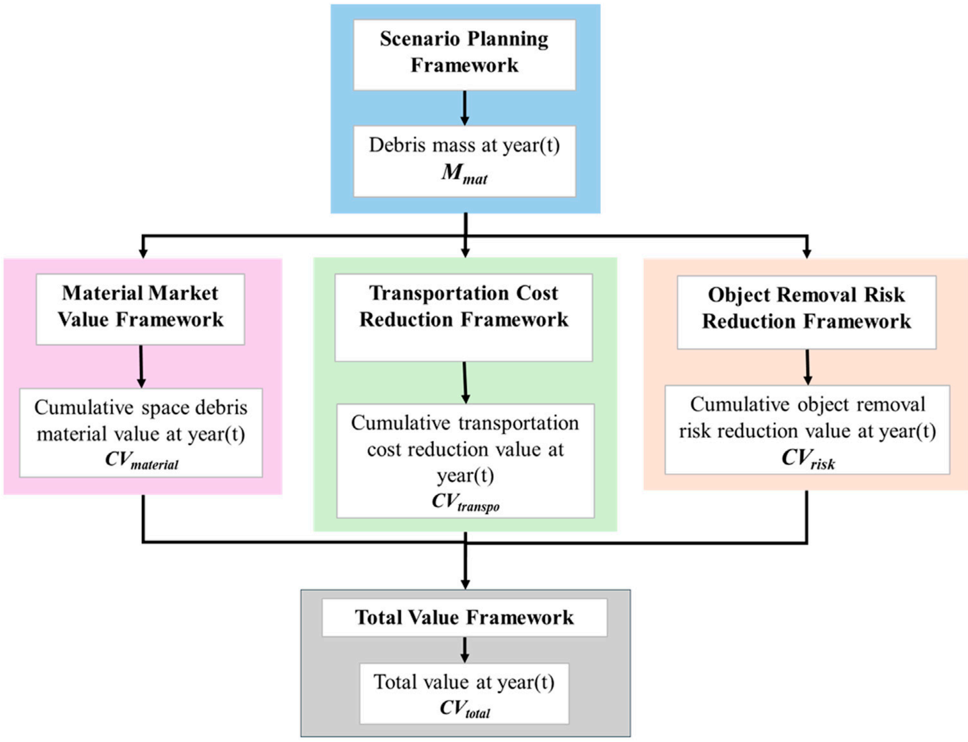

FIGURE 9
Total value framework flowchart illustrating the relationship among components that comprise the comprehensive value.

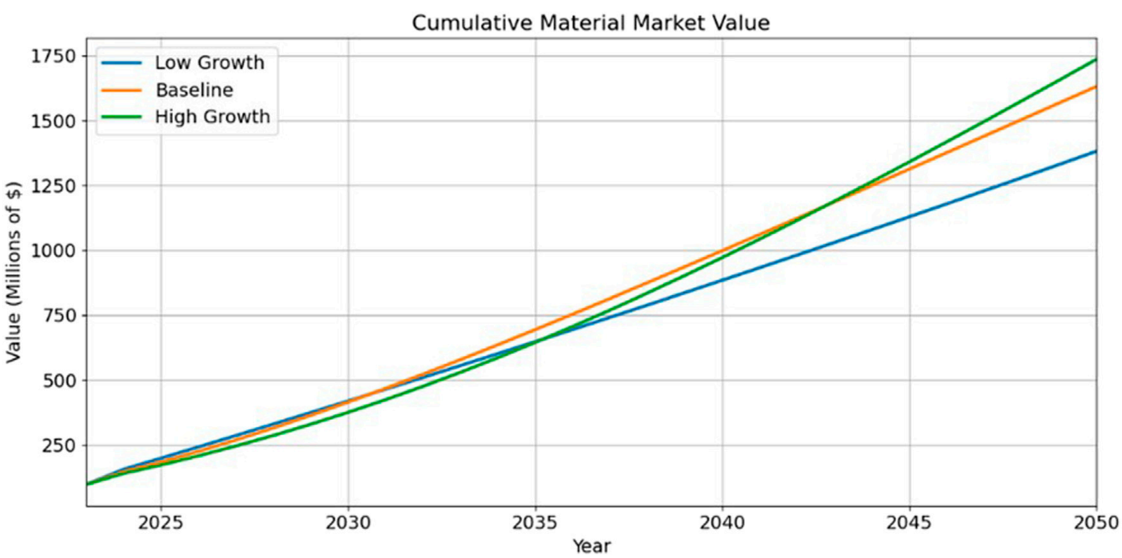

FIGURE 10
Cumulative material market value of space debris through 2050 across Low Growth, Baseline, and High Growth launch scenarios.

estimating an average replacement cost for this technology. As a result, the average replacement cost of a random catastrophic collision in LEO was estimated to be $96 million (Zhu, 2022).

2.4.5 Object removal risk reduction framework

The structure of the object removal risk reduction framework is informed by the methodology developed by Vance and Mense (2013) in their orbital debris removal value analysis. The first step

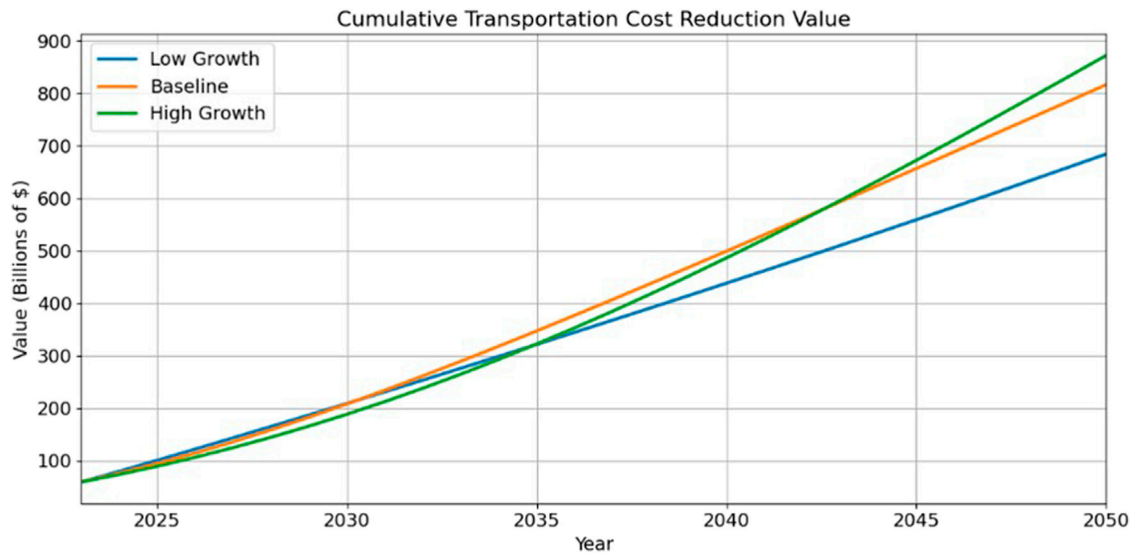

FIGURE 11
Cumulative transportation cost reduction value of space debris through 2050 across Low Growth, Baseline, and High Growth launch scenarios.

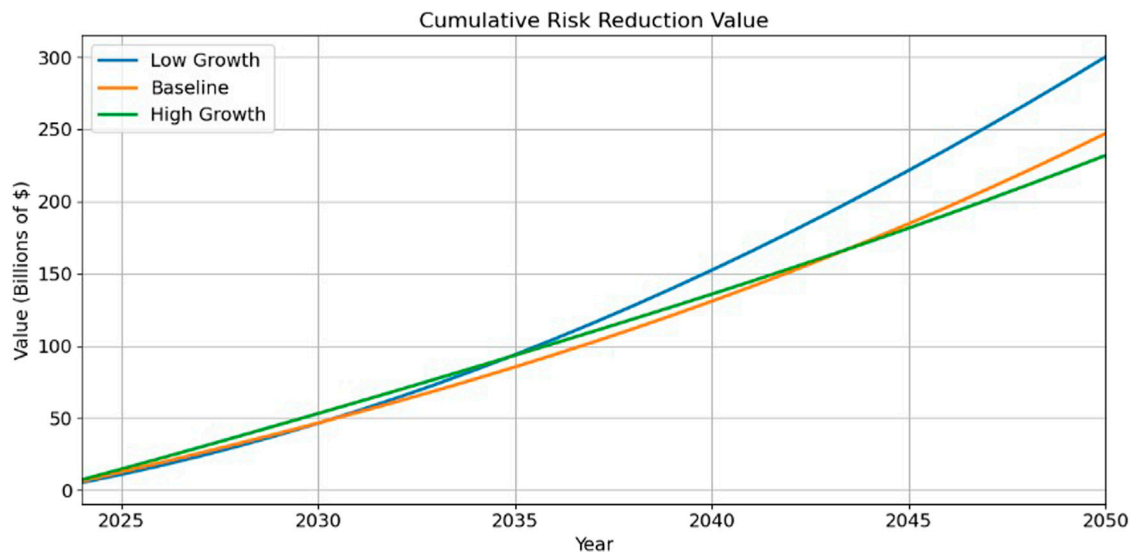

FIGURE 12
Cumulative object removal risk reduction value of space debris through 2050 across Low Growth, Baseline, and High Growth launch scenarios.

in the framework involves establishing a relationship between the predicted annual number of collisions and the overall space debris population. This relationship is outlined in Sections 2.4.1 and 2.4.2, resulting in the collision-to-mass ratio expressed in Equation 14.

This collision-to-mass ratio is then multiplied by the estimated replacement cost per collision (*TechReplaceCost*) (Section 2.4.4) and the expected annual amount of debris removed by ADR systems (*ADRDebRemoval*) (Section 2.4.3) to calculate the risk reduction value per year. These values are then aggregated annually to compute the cumulative risk reduction value (CV_{risk}) through the year 2050, as shown in Equation 15. A visual representation of this framework is provided in Figure 8.

TABLE 5 Total and itemized values for each component of the framework based on the launch rate scenario.

Launch rate scenario	Material market value	Transportation cost reduction value	Risk reduction value	Total value
Low growth	$1,364,380,700	$684,090,071,715	$300,244,679,889	$985,699,132,305
Baseline	$1,616,865,572	$816,256,771,521	$247,087,818,523	$1,064,961,455,616
High growth	$1,723,405,348	$872,026,491,558	$231,903,858,779	$1,105,653,755,686

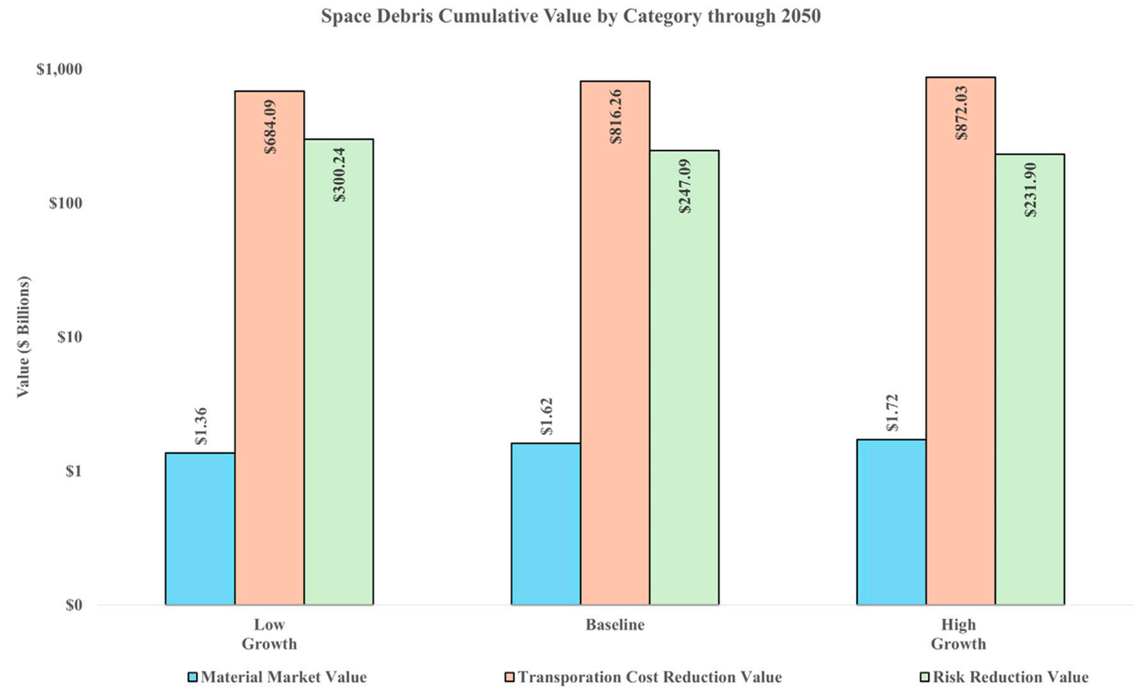

FIGURE 13
Total value of space debris by category through 2050 across Low Growth, Baseline, and High Growth launch scenarios.

$$CollisionToMassRatio\ (t) = \frac{0.90PMD(Collisions, t) - 0.99PMD(Collisions, t)}{0.90\ PMD\ (Mass, t) - 0.99\ PMD\ (Mass, t)} = \frac{\#Collisions\ (t)}{Space\ Debris\ Mass\ (\ t)} \tag{14}$$

$$CV_{risk} = \sum_{t=1}^{25} ADRDebRemoval * 50\ ADR\ Systems * \frac{\#\ Collisions\ (t)}{Space\ Debris\ Mass\ (t)} * \frac{TechReplaceCost}{Collision} \tag{15}$$

2.5 Total value equation

After calculating each subcomponent that contributes to the value of the space debris population, the aggregate of these results was taken to help project the total value under different launch rate scenarios. Figure 9 presents the outputs in this way to help illustrate how the overall perceived value of space debris varies based on projected launch activity. The total value for each scenario (CV_{total}) is calculated in Equation 16 by summing the outputs of the three preceding value components: material market value, transportation cost reduction value, and object removal risk reduction value.

$$CV_{total}\ (t) = CV_{material}\ (t) + CV_{transpo}\ (t) + CV_{risk}\ (t) \tag{16}$$

3 Results

3.1 Material market value

The cumulative material market value for the Low Growth, Baseline, and High Growth scenarios is estimated at $1.00 billion, $1.17 billion, and $1.24 billion, respectively. The cumulative annual material market trends for each scenario are shown in Figure 10,

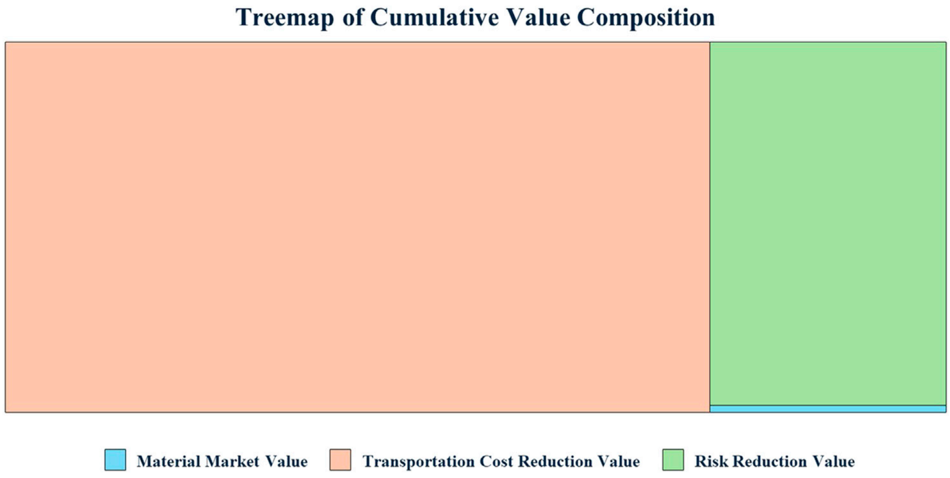

FIGURE 14
Relative composition of the total value of space debris based on the three analyzed sources of value.

TABLE 6 Total value sensitivity to variables of interest.

Framework variables	Low value	High value	Change to total value (%)
Space debris Mass (1957–2023)	4,187 kg	9,769 kg	6.74%
ADR systems	30*(1−0.198)	(50 + 3(t))*(1−0.066)	13.84%
ADR annual costs per system	$17,079,180	$39,851,420	4.38%
Annual launch cost reduction	2.64%	6.16%	3.21%
ADR system Mass removal per year	9,351 kg	26,475 kg	2.03%
Material degradation rate	60% of assumed rates	140% of assumed rates	0.21%
Material value ($/kg)	Lower bound scenario values	Upper bound scenario values	0.45%
Material value (1957–2023)	$58,200,000	$135,800,000	0.01%

illustrating that higher launch rates are associated with increased potential material value.

3.2 Transportation cost reduction value

The cumulative transportation cost reduction value for the Low Growth, Baseline, and High Growth scenarios is estimated at $684.09 billion, $816.26 billion, and $872.03 billion, respectively. The cumulative annual trends in transportation cost reduction value for each scenario are shown in Figure 11. These results indicate that higher launch rates are associated with greater potential for reducing material transportation costs in the future.

3.3 Object removal risk reduction value

The cumulative object removal risk reduction value for the Low Growth, Baseline, and High Growth scenarios is estimated at $16.49 billion, $13.22 billion, and $10.48 billion, respectively. The cumulative annual trends for each scenario are shown in Figure 12. These results indicate that lower launch rates are associated with higher risk reduction value when identical probabilities of collision and consistent ADR capabilities are applied across all scenarios. This outcome occurs because smaller debris populations result in each piece of debris representing a higher relative risk. Consequently, removing the same number of debris objects yields a greater overall risk reduction value in lower-growth scenarios compared to those with larger debris populations.

3.4 Total value

The total estimated value of utilizing the space debris population as a material source for in-space manufacturing under each launch rate scenario is presented in Table 5. The cumulative value for the Low Growth scenario is significantly lower than that for the Baseline and High Growth scenarios. This range of values provides both upper and lower bounds for evaluating the economic viability of reusing space debris in in-space manufacturing. Additionally, the proportional contribution of each value component to the cumulative total for each scenario is illustrated in Figure 13. The relative composition of each source of value to the cumulative value total is illustrated in Figure 14. This comparison highlights the relative perceived value of each component, indicating that the estimated transportation cost reduction value significantly outweighs the contributions from material value and risk reduction.

3.5 Sensitivity analysis

Given the high variability of the parameter values used to estimate the future comprehensive value of space debris in this framework, a sensitivity analysis was conducted to assess how changes to key parameters affect the cumulative value under the Baseline launch rate scenario. Within the sensitivity analysis, the previously defined lower and upper bound scenario values were applied to the ADR systems quantity (Section 2.3.4) and material value ($/kg) variables (Section 2.2.1). The remaining parameters were varied by ±40% of their original values, and the corresponding absolute relative change in the cumulative space debris value was calculated.

The summarized results presented in Table 6 indicate that variations in the quantity of operational ADR systems deployed annually have the most significant impact, altering the total cumulative value by approximately 13.84% in either direction. In contrast, the parameters that have the least influence on the framework's output are the material degradation rates and material values which would only change the cumulative space debris value by at most 0.21% and 0.45%, respectively. These findings are valuable in identifying which parameters most significantly influence value estimates and should be prioritized for refinement as more accurate data becomes available.

4 Discussion

4.1 Interpretation of results

Although this framework relies on several simplifying assumptions, interpreting its results provides insights into future decisions regarding space debris remediation. One key takeaway is that the reduction in transportation costs and risk-related costs has a much larger impact on the cumulative value than the market material value component. This suggests that the cumulative value is driven less by the material's inherent worth and more by its accessibility in the space environment, suggesting that recycling space debris is less economically viable for sustainable space practices than separately pursuing debris removal and resource extraction from celestial bodies. Since the material value of space debris is relatively low, this approach would still reduce collision risk through debris removal while directing investments toward infrastructure supporting resource extraction rather than debris recycling.

However, the implementation of this framework ultimately depends on the availability of large-scale ADR development and in-space manufacturing infrastructure. Realizing the benefits associated with the value of the space debris population requires substantial technological advancement, international coordination, and investment in capabilities that are currently in early development. Therefore, the results of this framework should be viewed as indicative of long-term opportunity rather than short-term feasibility.

Building on these results, it is important to consider how each value component—transportation cost reduction, material market value, and risk reduction—can be used to encourage investment in debris remediation infrastructure. An example of this includes being able to supply in-space manufacturing operations with material at a significantly reduced operational cost by avoiding the need to launch that material from Earth. However, applying this same economic incentive principle to the risk reduction value is more challenging. There is no direct transaction that occurs when space debris is removed from LEO, even though such removal inherently reduces the risk of collision for active space technologies. This may introduce a need for mechanisms such as a space tax system, which would require companies and organizations operating technology in LEO to pay annual fees to fund ADR services.

4.2 Limitations

This framework analyzes three distinct sources of value to provide a comprehensive understanding of the potential economic benefits of utilizing space debris for future in-space manufacturing processes. However, it relies on the assumption that ADR technology and in-space material processing and manufacturing capabilities will be deployed. While significant progress has been made in ADR development over recent years, widespread deployment of technology capable of large-scale debris removal from LEO has yet to be achieved. Additionally, although the space community is working towards the development of in-orbit and lunar manufacturing facilities, current in-orbit manufacturing capabilities consist primarily of 3-D printing systems, and lunar manufacturing remains largely conceptual (Abdulhamid et al., 2025).

Another limitation of this framework lies in its reliance on assumed average values for key parameters when estimating the future value of space debris in each scenario. The values of these parameters are likely to vary each year and may differ significantly from the averages used, which are derived from prior research and historical data. Throughout the framework, average values are used to approximate the influence of key parameters in the value calculations, acting as reasonable estimates based on historical trends. While this introduces some inaccuracy into the scenario-based calculations presented in this paper, the primary contribution is the development of a flexible framework for evaluating the potential economic viability of space debris as a resource for in-space manufacturing. As more updated parameter values become available, they can be incorporated into the framework and corresponding equations to improve the precision of value estimates.

A further limitation of this framework is its dependence on future policy and investment decisions that would impact the large-scale implementation of ADR operations and in-space processing capabilities. The realization of these modeled outcomes will require coordinated infrastructure development supported by collaboration between countries, commercial motivation, and regulatory alignment. Without these efforts, the projected value estimates may remain largely theoretical.

Due to limited available data on space material degradation, this framework primarily considers the erosion impact of atomic oxygen. However, ionizing radiation, ultraviolet radiation, and thermal cycling also contribute significantly to material degradation in space. Although research regarding the effect of prolonged exposure of different materials to various LEO environmental conditions is limited, existing studies indicate that continued exposure to the space environment leads to increasing levels of material degradation and a corresponding decay in structural integrity (Samwel, 2014). Therefore, the length of time that space debris material is exposed to the LEO environment impacts its ability to be recycled for in-space manufacturing applications. It would be beneficial for future research to examine material degradation rates while taking into consideration several space erosion factors to determine how degradation impacts material quality. This analysis would help improve the accuracy of estimates regarding the proportion of space debris that remains viable for reuse in in-space manufacturing.

4.3 Implications

The main goal of this framework was to establish a methodology that defines the relationship between key parameters needed to estimate the future value of the space debris population using data available to the user. Applying this framework to the Low Growth, Baseline, and High Growth scenarios helps illustrate the range of space debris value that may be possible, given the uncertain nature of future annual space launch quantities. Over the next decade, the space economy is expected to reach $1.8 trillion due to the broadened application of space-based services across various industries (Schmidt and Thomas, 2025). The ability to estimate the economic viability of recycling space debris is a valuable capability given the growing focus on investing in the development of in-orbit services and in-space manufacturing.

To translate these findings into actionable strategies, policymakers and investors could use this framework to identify where investments would be most effective in supporting debris remediation efforts. Much like how electric vehicle manufacturers and consumers were subsidized to accelerate the adoption and development of this technology, governments could use the framework's calculated debris value as a guideline for helping price monetary incentives for ADR technology demonstrations and implementation. Drawing from the carbon pricing model, which assigns a financial cost to the risk associated with certain levels of carbon emissions, regulatory mechanisms could similarly use the framework's calculated risk reduction value to fund debris removal initiatives through orbital-use fees. Additionally, space agencies and commercial operators could use the model's results to prioritize the alignment of technological development with economic opportunity.

Despite the growing commercial interest in space, the accumulation of space debris threatens the sustainability of future space operations. One of the main issues in securing support for space debris remediation efforts is the lack of economic incentives associated with proposed solutions. This framework helps address that gap by quantifying the potential total value of reusing space debris material and breaking it down into its three primary sources of value. The results help potential stakeholders understand where the most significant economic opportunities lie when investing in debris remediation infrastructure. By highlighting the economic drivers of sustainability in space, the model can serve as a cost-benefit tool for stakeholder decision-making, helping them compare trade-offs between investment in ADR, in-space manufacturing, and policy interventions. In turn, these investments could support the economic viability of establishing a circular space economy, leading to a more sustainable future for space exploration.

5 Conclusions and recommendations

This framework fills a gap in the literature by providing a method to estimate the total value of space debris material in LEO and offering a clearer understanding of its economic viability if used as a material sourcing option for in-space manufacturing. Based on the results, the most significant opportunity for value in reusing space debris lies in the cost savings associated with reducing material transport to space. The cumulative value estimates across the different scenarios range from approximately $701 to $884 billion, corresponding to approximately 38%–49% of the expected space economy value over the next decade (Schmidt and Thomas, 2025). Although these estimates are derived from key assumptions, they suggest that the economic viability of reusing space debris is possible with the development of in-space manufacturing systems.

As more information about the space debris system becomes available, values within this framework can be continually refined to produce more accurate total value predictions. In addition to reducing uncertainties in the data, future work could apply this framework to the most hazardous pieces of space debris to evaluate economic incentives associated with prioritizing their removal. Future studies could also expand upon this framework by comparing the costs and benefits of infrastructure needed for space debris remediation with those for resource utilization from celestial bodies. Such analysis would provide a more comprehensive understanding of which solutions are most economically viable for the future of sustainable space exploration.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ML: Investigation, Methodology, Writing – original draft, Writing – review and editing, Data curation, Formal Analysis, Visualization. SB: Investigation, Methodology, Writing – original draft, Writing – review and editing, Conceptualization, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that Generative AI was used in the creation of this manuscript. AI tools were used to assist in grammar review during the preparation of this manuscript. The models used were GPT-5 (OpenAI), accessed via web interface, and Grammarly's AI-powered writing assistant (Grammarly Inc.). The specific prompt used during the review process was "check this text for grammar and redundancy, apply minimal changes so that the original tone and content remain intact.

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