In-Space Manufacturing: An Evaluation of the Economic Viability

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Abstract: In an ever-evolving global economy, in-space manufacturing is emerging as a frontier for unprecedented opportunities and challenges. This research paper analyzes the in-space manufacturing economy, exploring its significance and role within the current global economic landscape. Utilizing a qualitative methodology, the study provides a holistic view of the economic evolution, spotlighting the technological transition and shift towards contemporary and futuristic economic paradigms. It identifies the space economy as an emerging economic opportunity characterized by global security tension, financial pressures, and the pursuit of economic diversification. The research highlights the escalating global competition within the space sector, emphasizing its rapid expansion and broader socio-economic implications. Preliminary findings underscore the critical role of advanced technologies, space tourism, and the investment of private sector actors such as SpaceX and BlueOrigin, illustrating a significant shift towards technology-driven commercial dominance in the space economy. This paper is part of an ongoing work to develop and advance in-space manufacturing. It contributes to the strategic implications of space exploration by advocating for a robust regulatory framework to ensure sustainable development. It also mitigates space exploration risks across social, economic, military, and security dimensions. This economic analysis elucidates the space economy's pivotal role in shaping future economic development and international collaboration, offering a reference source for policymakers, industry stakeholders, and academic researchers.

Keywords: Space Economy, Manufacturing in Space, Space Resources Utilization, Space Mission Lifecycle, Economic Analysis

1. Introduction

In-space manufacturing (ISM) has emerged as a potentially viable supportability strategy for future human spaceflight missions. In this context, ' supportability' refers to a system's design characteristics that allow for efficient logistics and maintenance, ensuring safe and effective operations in orbit (Owens et al., 2017). ISM, as currently conceived, would enable manufacturing components directly in space, leveraging resources harvested from the space environment or repurposing secondary materials. This innovative solution to manufacturing addresses the logistical challenge of launching and storing spare parts by allowing on-demand production using specialized or common raw materials(Abdulhamid et al., 2023). The realization of ISM could facilitate a paradigm shift in space systems, providing greater flexibility and optimized performance, resulting in more adaptable systems capable of operating well beyond the traditional 15-year lifespan of satellites and the impressive 42-year planned life of the International Space Station (Hepp et al., 2014; Sanders & Kleinhenz, 2023).

ISM also represents one of the cornerstones for sustainable human space missions. By manufacturing goods on-demand in space, ISM eliminates the need for detailed pre-mission planning for every potential failure, decreasing the payload and storage needs and simplifying inventory management. Additionally, ISM aligns with Circular Manufacturing strategies, enabling the creation of a self-sustaining industrial ecosystem. Through the ability to harvest and recycle space debris through In-Situ Resource Utilization (ISRU), ISM promises to reduce the dependency on Earth's resources while simultaneously addressing space waste concerns (Hepp et al., 2014). ISM's role in the future space economy extends to its potential to reshape the mission definition, launch vehicles, supply chain dynamics, and sustainability of Low-Earth Orbit (LEO) manufacturing. Studies(Kringer et al., 2022) within the field have developed assessment frameworks to evaluate materials, additive manufacturing techniques, and advanced manufacturing processes for space applications; however, due to the vast degree of technical uncertainty, the economic viability of such an endeavor has mainly been generalized up to now.

1.1 Scope and Objectives of the Research

This research aims to analyze ISM's potential economic feasibility to forge a path for Factory in Space Systems (FIS). Considering the resource limitations in isolated space environments, such as orbital colonies or stations, it is essential to embrace methodologies that extend the utility of materials and goods across multiple lifecycles. The research is anchored in establishing a closed-loop system that minimizes Earth-dependence for resupply missions and upholds ethical standards regarding space waste and LEO operations.

To address these objectives, this paper will explore the economic viability, opportunities, and risks associated with the ISM. The model aims to encapsulate the intricate web of factors influencing FIS facilities' design, implementation, and operation, focusing on the products/components that can be manufactured. Through this, the paper offers insight into the economic feasibility of FIS.

2. In-Space Manufacturing

Manufacturing within LEO is a concept that has evolved significantly since the historic servicing missions to the Hubble Space Telescope (HST) in the 1980s. These missions established in-space servicing as a viable means to extend the operational life of space assets. Underscoring the potential cost savings and mission benefits of in-orbit manufacturing capabilities (Abdulhamid et al., 2024). The HST's design-for-repair structure allowed astronauts to replace failing components, extending the telescope's mission life beyond its planned 15-year lifespan.

These early missions to autonomous in-space activities were marked by the "Orbital Express" project of 2007, funded by DARPA. It demonstrated robotic satellite servicing, including autonomous assembly capabilities. This progress was paralleled by NASA and ESA's development of sophisticated robotic arms, indicating a strong interest in autonomous technologies for space applications.

The parallels between early LEO manufacturing efforts and transformative technologies like Additive Manufacturing (AM) are particularly striking. The ability of AM to produce ready-to-use parts from stock material makes it a pivotal technology for ISM. NASA's initiative, "AM in Space," culminated in the installation of the first AM system aboard the ISS in 2014 under the "3D Printing in Zero-G" project (Zocca et al., 2022). The subsequent introduction of the Additive Manufacturing Facility (AMF) in 2016 advanced these efforts, utilizing knowledge gained from AMF operations to expand FIS capabilities.

NASA's Restore-L, later known as the On-orbit Servicing, Assembly, and Manufacturing Mission (OSAM-1&2), reflects the agency's dedication to advancing ISM. OSAM-1's infrastructure enables satellite refueling, antenna assembly, and beam manufacturing, while OSAM-2's technology demonstration mission was completed in 2023. In parallel, the EU's focus on sustainability has manifested in projects like the AMAZE initiative, which explored in-situ manufacturing possibilities in extraterrestrial settings, including the moon and asteroids. Launched in collaboration with ESA and the Manufacturing Technology Centre (MTC), AMAZE's methodologies were demonstrated in pilot factories across Europe. A detailed review of ESA's manufacturing activities was presented (Makaya et al., 2023).

Meanwhile, the China Academy of Space Technology made strides with the development and successful LEO testing of its Space-based Composite Material 3D Printing System aboard the Long March 5B heavy-lift carrier rocket in 2020. This system employs carbon-fiber-reinforced composites for autonomous in-space object printing (Ministry of National Defense of the People's Republic of China, 2020). Additionally, private sector involvement has been crucial in transitioning FIS from conceptual to operational. Companies like Redwire (formerly Made in Space) have been instrumental in the AMF's development on the ISS and subsequent OSAM missions. Similarly, Northrop Grumman's contributions through the Mission Robotic Vehicle (MRV) and the Mission Extension Vehicle (MEV) deployment have underscored the private sector's ability to deliver innovative solutions for FIS. Thales Alenia Space (TAS) is also developing a satellite with manufacturing capabilities, with a demonstration expected in 2026.

2.1 Key Drivers of ISM

Private enterprises, such as SpaceX and BlueOrigin, have significantly reduced the barrier to space with the introduction of reusable rockets and have galvanized the market with ambitious projects and innovative approaches to space travel and exploration. Emerging startups are also pivotal in pushing the boundaries of what's possible in space, contributing novel ideas and technologies that stimulate economic growth within the sector. This surge in private sector participation has diversified the industry and introduced new economic models and partnerships that enhance the feasibility and attractiveness of ISM ventures. A summary of the drivers of ISM is shown in Table 1.

Table 1: Drivers for ISM

Driver	Description
Decreased Launch Costs	The advent of reusable launch vehicles and increased competition has led to a reduction in the cost of accessing space.
Technological Advancements	Robotics, automation, and AI are advancing ISM capabilities, allowing for more complex and reliable space operations.
Private Sector Investment	Increased investment from private companies in space technologies and infrastructure.

2.2 Economic Opportunities

ISM offers the potential to manufacture products in microgravity conditions, which can offer significant advantages over Earth-based production. Table 2 summarizes the potential products and their benefits when manufactured in space (James, 2022).

Microgravity enables the production of ultra-pure pharmaceuticals by eliminating sedimentation and convection processes that can introduce impurities. Similarly, the manufacture of complex materials and perfect crystals is improved in space, where the absence of gravity prevents the formation of defects commonly found in gravity-bound processes.

Table 2: Products and Opportunities

Product	Benefits of Microgravity Manufacturing
Pharma	Ultra-purity, enhanced crystal growth
Advanced Alloys	Improved structural integrity, absence of sedimentation
Crystals	Defect-free materials for electronics and optics
Fiber Optics	Better quality, fewer imperfections

3. Risks and Uncertainties Associated to Scenario

As described in Section 2, ISM has the potential to offer numerous benefits. However, the environment and system specifications also introduce various technical and economic challenges. These challenges include technological reliability and economic viability, each affecting the other and shaping the scenario (Table 3).

Table 3: ISM LEO Scenario

Scenario	Details
Market	ISM market demand analysis ($350B to $1T by 2040), sector growth (5-7% annually), target markets (satellite manufacturing, deep-space exploration).
Relevant Tech.	Additive manufacturing (laser sintering, stereolithography), autonomous robotics (ISS's Canadarm2), recycling/reprocessing (melt-processing, pyrolysis).

Req.	ISM operations assessment for scalability, adaptability, resilience (thermal resistance, radiation hardening).
LEO Env.	Documented LEO conditions (160-200 km to 2000 km), operational challenges (radiation, microgravity).
Debris	Tracked satellites (6768 operational) and debris (over 35150 objects), informing shielding requirements.

3.1 Technological and Operational Risks

Risks within any engineering endeavor can pose significant challenges; however, given space's unique and harsh conditions, special attention must be paid. System reliability is paramount, as equipment must function flawlessly under extreme conditions such as significant temperature fluctuations, high radiation levels, and microgravity. The behavior of materials in microgravity requires innovative solutions for material handling to prevent operational disruptions. Automation plays a crucial role in ISM due to the remote nature of operations, necessitating advanced robotics capable of performing complex tasks autonomously. Furthermore, ISM operations depend heavily on robust material handling capabilities, communication systems, and automation to mitigate the risks associated with delays and data integrity issues, which can compromise processes and operational efficiency.

Table 4: Space Material Management

Activity	**Description:**
(i) Debris collision risk technical approaches	
Space Situational Awareness (SSA)	Detect, catalog, and predict object orbits.
Space Traffic Coordination (STC) and Space Traffic Management (STM)	Plan, coordinate, and synchronize activities in space. Licensing and monitoring of spacecraft, as a supplement to STC.
Space Environment Assessment (SEA) and Space Environment Management (SEM)	Implement mitigation and remedial procedures once SEA has assessed the degree of risk and the cost-effectiveness, to prevent the propagation of uncontrollable space objects.
(ii) Debris population remediation activities	
Active Debris Removal (ADR)	Active removal of derelict objects to decrease collision probability.
Just-in-time Collision Avoidance (JCA)	External influence the trajectory of one of the two pieces of debris before collision time, to reduce collisions likelihood
Debris Resurrection (DR)	Nano-tugs to upgrade derelict objects with collision avoidance capabilities
(iii) Debris population mitigation activities	
In Space Manufacturing (ISM)	Reduction of the sources of space debris (e.g. avoiding explosions, increasing satellite reliability).

As shown in Table 4, the management of space materials relies on integrating various technologies and systems, such as a space tug. The tug, as such, is instrumental in this process, serving not only as a vehicle for transporting materials across different orbits but also as an essential tool for collecting and redistributing resources and debris. These tugs must have automation and robotics capabilities and interface with various systems (ISM for loading and off-loading, satellites for material extraction/collection/deployment). While central to the operational efficiency of the ISM, risks associated with their operation must be mitigated and managed to allow for safe and predictable operation.

3.2 Economic Risks

Economic risks in ISM stem primarily from the substantial initial investments required to develop, launch, and maintain manufacturing capabilities in space. The return on these investments is often uncertain and long-term, influenced heavily by evolving market demands and the commercial viability of space-manufactured products. Additionally, the complexity of establishing a reliable supply chain for transporting materials to and from space or sourcing them in-space adds another layer of economic uncertainty. Regulatory and legal frameworks, as detailed in Section 3.3, also present significant risks, as they are still under development and can affect operational permissions and the broader adoption of ISM technologies. Effective management of these economic challenges is critical for achieving sustainable operations and requires continuous evaluation of market trends, technological advancements, and regulatory changes.

3.3 Regulatory Uncertainty

FIS operations, especially commercial activities, require a regulatory body to govern them. This is quite an unusual burden, considering on-orbit manufacturing is still in its demonstration phase. The US law, for instance, partially addresses this topic but does not address the launching and establishment of FIS facilities. Currently, components manufactured in space fall into a regulatory gap. The challenge with international space law is the recognition of space resources as legally acquirable and that objects produced in space - similar to satellite constellations in LEO - can become a mainstay of extraterrestrial explorations. The concepts and challenges of FIS have been closely linked with that of space debris. Hobbs et al. (Hobbs et al., 2019) argue that FIS overlaps with debris removal activities and share the same concerns. Therefore, it can be argued that the existing space law, established before the conception of FIS, is outdated and a hindrance to the actualization of FIS. Similarly, the question by Hobbs et al. can be mapped to a FIS context such that it becomes; "what to manufacture, how to manufacture, who manufactures, when to manufacture, and who pays for it." It can then be concluded that there needs to be a legal framework that governs the establishment of FIS.

Furthermore, the ongoing phase 5 (2018-2033)(Jackson & Joseph, 2021) of the space industry development needs to introduce a series of new actors and stakeholders to shift the sector from its traditional definitions. For instance, Paladini et al. (Paladini et al., 2021) developed a framework for integrating the circular economy, the space sector, and Industry 4.0. However, Industry 4.0 is at its peak when all nine fundamental pillars (i.e., Big data & AI, Horizontal and Vertical Integration, Cloud Computing, AR, IoT, AM and 3D Printing, Autonomous Robot, Simulation, and Cyber-Security) are in synchrony. The ongoing development phase must leverage globalization and the digital revolution to develop a framework for easy access to space information and data.

4. ISM Economic Assessment

The costs of designing, launching, and operating an ISM system could range from $2 billion to over $140-160 billion (Skylab, Tiangong, ISS), depending on the mission, environment, and capabilities included (Crane et al., 2020). Therefore, the economic assessment of such a system must consider technical, financial, operational, and market scenarios when considering and assessing viability.

4.1 Operating Specifications

The ISM must overcome demanding conditions unique to its operational environment. These conditions influence the system's design, development process, operational strategy, and lifespan. The abridged specifications outlined here aim to facilitate the evaluation of the system while ensuring robustness, adaptability, and feasibility.

- **Environment**: the environment is characterized by unique and challenging conditions at an altitude ranging from approximately 400 to 900 kilometers above Earth. The ISM would be exposed to a harsh mix of extreme temperatures, microgravity, and a higher flux of ionizing radiation from the Van Allen belts than Earth's surface. The temperature in LEO can vary dramatically, from +250 degrees Fahrenheit (+121°C) in direct sunlight to -250 degrees Fahrenheit (-157°C) in the shadow of Earth, necessitating robust thermal control systems to protect sensitive electronics and materials. Although thin, a residual atmospheric drag also affects the system, gradually decreasing its orbit over time and demanding periodic adjustments to maintain altitude. Furthermore, the microgravity environment impacts fluid behavior, influencing the design of mechanical fluid management systems. Collectively, these conditions define the operational context for LEO space systems, guiding the engineering and operational strategies to ensure mission success and safety.
- **Specifications**: The ISM system shall be capable of high operational efficiency with minimal human intervention. This includes flexibility to accommodate various manufacturing processes and product demands.

  The design should accommodate future technological advancements and expansion in manufacturing capabilities. This flexibility is crucial for adapting to evolving mission needs and incorporating innovations. Given the remote and challenging conditions, high system reliability is vital. The system should be designed for ease of maintenance and repair, considering autonomous operations when direct human intervention is not feasible.

4.2 Products

Products encompass and represent opportunities across various markets and applications, from aerospace components to biomedical products (Table 2).

- **Volume of Products:** The volume of products manufactured in space, Vp(t), is a metric for assessing the throughput and efficiency of the ISM system over time. An increase in the variable represents technological improvements, process optimization, and system resource availability.
- **Product Variety:** The variety of products, N(t) includes customized tools for astronauts, components for satellite repair, or even complex structures for spacecraft. An increase in the variable can indicate the flexibility of the ISM equipment and advancements in the associated technologies.
- **Costs:** *Cp(t)* includes expenses per product unit, incorporating raw materials, labor, and overhead.
- **Selling Price** *P(t)* represents the relative price for which the manufactured product/component is sold.
- **Revenue:** *R*(*t*) represents the revenue generated from selling the products manufactured in space and is equals $Vp(t) \cdot N(t) \cdot P(t)$

4.3 Associated Costs

ISM is expected to be capital-intensive due to the system's intricate and highly technical demands. Therefore, various costs across different project lifecycle phases are to be expected. Each phase has specific financial implications, From development through launch to the operational maintenance of the systems.

4.3.1 Development

Development costs of the ISM encompass all expenses related to the R&D of technologies suitable for use in the space environment. This includes the costs of:

- Development cost *Cd*(*t*), accumulated by time *t*, including research, design, and initial setup.

4.3.2 Launch and Deployment

The launch and deployment phase covers all costs of getting the ISM system into space and operational. This includes:

- Launch costs *Claunch*(*t*) represents the cost for launching payloads to space, calculated per kilogram.
- The cost of acquiring or leasing launch vehicles depends on their reuse capability *Clv*(*t*).
- General costs incurred for deploying space-manufactured modules or platforms *Cdeploy*(*t*).

4.3.3 Supply Chain and Materials

Managing the supply chain and materials for ISM can involve complex logistics and be an expensive space manufacturing element. Representing:

- Logistics and supply chain costs, mainly from Earth to space, transport *Sl*(*t*).
- Savings from using space-based resources instead of Earth resources *Ss*(*t*).
- Costs associated with recycling used materials or decommissioned satellites on board the ISM *Cr*(*t*).
- Mass of materials recycled per year *Mr*(*t*).
- Cost of processing materials in situ, which includes extraction and refinement *Cm*(*t*).
- Mass of in-situ materials processed each year *Mm*(*t*).

4.3.4 Operation and Maintenance

The operational phase includes ongoing costs associated with running and maintaining the ISM system:

- Costs for maintenance, service, and system upgrades to ensure operational efficiency are *Cmsu*(*t*).
- Operational costs, including day-to-day running of ISM facilities, staff costs, and in-orbit operations, *Cop*(*t*).
- The financial impact due to downtime or operational delays incurred, *D*(*t*).
- Non-recurring costs that occur at project setup or during major upgrades *Cnrc*(*t*).
- Regular recurring costs are needed for ongoing operations *Crc*(*t*).

4.4 Financial Metrics and Analysis

The preliminary model integrates various cost factors such as development, production, maintenance, launch, and operational costs, along with revenue generated from the products manufactured in space and the impact of recycling and in-situ resource utilization, which are critical to sustainability in space environments. Through this, the model approximates the financial dynamics of ISM.

By allowing for the adjustment of the variables over time, the model aims to support long-term planning. These changes will enable it to adapt and accommodate market fluctuations, technological advancements, and policy changes. Net Present Value (NPV) is used to calculate the ISM project considering the various cash inflows and outflows, adjusted for the time value of money and inflation (static in this model).

4.4.1 Initial Variables

- *t*: Time variable representing each year within the project timeline.
- *T*: Total duration of the project analysis.
- *i*(*t*): Discount rate, reflecting the time value of money and investment risk.
- Inf(*t*): Inflation rate affects future cash flows' actual value.

4.4.2 Economic Functions

- **Profit** $\prod(t)$

$$\prod(t)=R(t)-[Cop(t)+Cmsu(t)+Claunch(t)+Clv(t)+Cp(t)\cdot Vp(t)+Cr(t)+Mr(t)+Cm(t)+Mm(t)+Sl(t)+Ss(t)+D(t)]+Cnrc(t)+Crc(t)]$$

The model calculates annual profits by subtracting the sum of various costs from the revenue generated each year. This includes the direct production costs and indirect costs such as maintenance and logistics.

- **Repayment** Q(*t*)

$$Q(t) = \int_0^t \prod(\tau)e^{-\int_0^\tau i(u)du}d\tau - C_d \cdot e^{-\int_0^t i(u)du}$$

It calculates when the ISM project would break even or generate a net positive cash flow. This is crucial given the high capital investment and the potentially long timeline for the return on capital.

- **Net Present Value** NPV

$$\begin{aligned} NPV &\\ = \int_0^T & [\prod(t) - C_{op}(t) + C_{msu}(t) + C_{launch}(t + C_{lv}(t) + C_p(t)\times V_p(t) + C_r(t)\times M_r(t) \\ &+ Cm(t)\times Mm(t) + Sl(t) - Ss(t) + D(t) + Cnrc(t) \\ &+ Crc(t))]e^{-\int_0^t (i(\tau)+Inf(\tau))d\tau} - Cd \end{aligned}$$

NPV accounts for the time value of money by discounting future cash flows back to their present value using a specified discount rate. A positive NPV suggests that the project is expected to generate a profit over its lifetime, taking into account initial and ongoing costs.

4.4.3 Assumptions

The model is built on several key assumptions that underpin the forecasts for revenue and costs:

- Revenue and cost projections are based on current market analyses and expert forecasts.
- Discount and inflation rates are based on historical economic data and expected market trends.
- The operational life of the ISM is estimated based on technological durability and economic feasibility.

4.4.4 Limitations

While the model aims to provide insight into the economic viability of ISM projects, it is subject to several limitations:

- Market fluctuations and technological disruptions could significantly impact cost and revenue estimates.
- Regulatory changes could introduce unforeseen costs or barriers.
- Estimation errors in the initial parameters could lead to significant deviations in projected outcomes.

5. Theoretical Use Case

To advance the research and provide an understanding of ISM's potential financial dynamics and viability, a simplified theoretical use case has been developed and used to apply the preliminary model (Section 4). This use case, while simplified, is based on the operational and economic parameters outlined in the financial model and details provided by ongoing space system development.

- *T*: 50 years
- *i*(*t*): 5% per year
- Inf(*t*): 2% per year

5.1 Operating Specifications

Based on the system's life span, a set of operational specifications have been established according to the system's environmental conditions. As stated in Section 4.1, these specifications ensure the system's functionality, sustainability, and efficiency in LEO. By integrating advanced technological solutions and robust design principles, the ISM system is positioned to efficiently exploit space manufacturing opportunities while mitigating its environment's inherent risks. Table 5 provides a summary of the operation specifications.

Table 5. LEO environment: parameters and description

Parameter	Description
Atmospheric Pressure	Negligible, vacuum conditions prevail within modules (roughly 10–700 nPa)
Atmospheric Drag	Despite the low atmospheric density, atmospheric drag is a relevant factor for station-keeping and orbit maintenance.
Propulsion	The manufacturing system must include propulsion capabilities or regular boosts from auxiliary vehicles to counteract orbital decay.
Attitude	Adjustable - Controlled to optimize solar power and communication links. Approx. 51.6 degrees
Altitude	400 to 900 km above Earth's surface.
Solar Radiation Level	Average of 1361 W/m², varies with solar cycle
Debris	1 to 10cm at 13 km/s

5.2 Products

Concerning the product, the objective was to define a product that was generally more fragile, not safety critical for the mission, and not placed near dangerous subsystems such as propulsion. The first study focuses on antennas.

A general set of values was proposed based on the S-band (from 2 to 4 GHz) helix antennas, generation 3 (G3). The product application would be used to produce new antennas for repair purposes. While made of aluminum alloy, the specific composition can be assessed by optimizing the in-orbit manufacturing process. The antenna material choice is generally influenced by communication performance and the need to withstand launch thermal and structural loads, depending on the satellite's configuration inside the fairing or the availability on-ground. In this case, the flexibility of decision-making is a benefit offered by a space factory.

Table 6. Initial Scenario Values

Variable	Value
Vp(t)	Starting Annual Production Volume = **500 units**
N(t)	Number of variations starts at **1** and increases by 1 every 5-years
Cp(t)	**\$10,000.00** x $(1 + \mathrm{Inf})^t$
P(t)	**\$15,0000.00** x $(1 + \mathrm{Inf})^t$

5.3 Associated Costs

Based on the challenges and opportunities of ISM (Section 5.1), hypothetical costs associated with ISM were established. Initial scenario estimate is shown in Table 6. The costs, as explained in Section 4, consider the system's life cycle. The cost breakdown was established using existing reference systems and represents a substantial initial investment, alongside recurring costs for launch operations, material supply, and maintenance. The details of the associated costs are emphasized in Table 7. Associated costs are estimated from historical data as such information is not readily available.

Table 7. Detailed Associated Costs of Scenario

Variable	Value
Cd(*t*)	\$20 billion
Claunch(*t*)	\$150 million annually
Clv(*t*)	\$100 million annually
Cdeploy(*t*)	\$500 million (initial year only)
Sl(*t*)	\$50 million annually
Ss(*t*)	\$20 million annually
Cr(*t*)	\$10 million annually
Mr(*t*)	100 tons ×(1 + Growth rate of 2%)t
Mm(*t*)	1.0×Mr(t) • 1.0 in this instance implies a direct one-to-one relationship where all recycled material potentially contributes to in-situ processing.
Cm(*t*)	100,000×Mm(t) • \$100,000 per ton
Cmsu(*t*)	$0.08t^2 - 2t + 200$ • 200 million (the initial high setup cost). • −2 million to illustrate a decrease over the first few years. • 0.08 million to reflect gradual cost increases starting more significantly after 20 years
Cop(*t*)	\$110 million annually
D(*t*)	\$10,000×(1+ rate 0.03)t×50 • Basic downtime - \$10,000 per hour initially • 3% increasing costs associated with more complex maintenance or higher stakes as technology advances. • 50hours of downtime per year
Cnrc(*t*)	\$100 million (occurs at significant upgrade intervals, e.g., every 10 years)
Crc(*t*)	\$27.5 million for recurring costs needed for ongoing operations, including minor updates.

5.4 Economic Assessment

Considering the theoretical use case presented in sub-Sections 5.1-5.3, an economic assessment as described in Section 4 was performed to gain theoretical insight into the financial dynamics associated with ISM. The models and preliminary outcomes presented in the following sub-sections represent the potential feasibility of ISM.

5.4.1 Profit

The model calculated the annual profit based on the variables and lifespan of the system. It was observed that there was no profit for the first 19 years; after the 20th year of operation, the ISM scenario started to generate profit, as shown in Figure 1. This delayed profitability is primarily due to the substantial upfront investments required for deployment and setup, which are amortized over an extended period. The step-like increases in profitability correspond to the project's ability to increase the number of products and variations N(t).

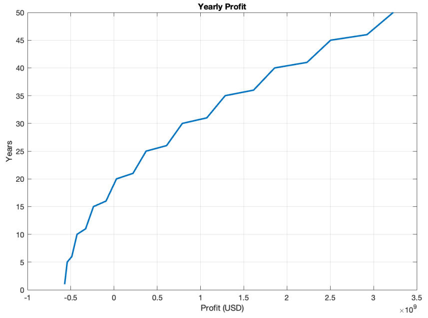

Figure 1. Yearly profit.

5.4.2 Repayment

Figure 2 indicates a break-even point in the 44th year based on the repayment model. Based on the current hypothetical scenario, the prolonged repayment period can be attributed to the required substantial initial investment in technology and infrastructure development, which is not quickly recouped due to the gradual scaling of production and product diversification. The system and model do not consider operational optimality or alternative revenue streams, which could accelerate cost recovery and enhance profitability. Lastly, given the project's reliance on traditional financing and cost structures, there needs to be more exploration of innovative funding mechanisms or partnerships that could offset initial costs and reduce financial risk earlier in the project lifecycle (launch vehicle, component modules, etc.).

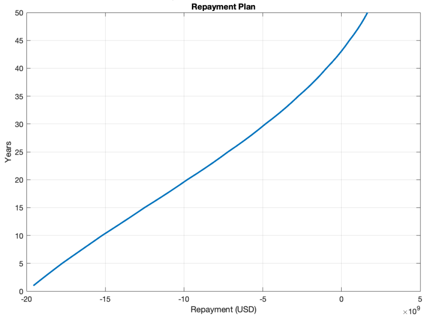

Figure 2. Repayment plan.

5.4.3 NPV

The NPV was calculated to be positive, with a value of 6.99e18, suggesting that the discounted future cash flows from the project outweigh the initial expenditures. This indicates that the hypothetical scenario evaluated would be expected to generate a profit over its lifetime, further enhancing the results of Figure 1&2 above.

5.4.4 Discussion

The assessment of the ISM scenario indicates that the venture would eventually lead to long-term profit. The life span of the ISS is comparable to that of the ISM scenario. Hence, the 50-year timeline makes achieving economic value from FIS ventures feasible.

The results and initial outcomes derived underscore the economic viability of a potential ISM projects. Where, strategic scaling of operations, diversification of product offerings, and enhancements in operational efficiencies are recommended to maximize economic impact. Key financial metrics such as profit, repayment periods, and Net Present Value (NPV) have been quantified through the models. These metrics show that a significant initial capital investment is required for a long period before achieving profitability, highlighting a risk-return profile critical for stakeholder evaluations. The models' year-by-year financial breakdown allows us to identify primary economic drivers: increased production volume, diversity in product offerings, and operational efficiencies. This can help identify strategic areas where resource allocation and innovation provide the highest financial returns.

Additionally, models and insights gained from the scenario can be helpful in scenario planning, enabling project managers to evaluate various economic conditions by adjusting inputs such as material costs, production efficiency, and market prices. This is essential for the further development of flexible operational strategies.

6. Conclusion and Future Work

In conclusion, the economic analysis presented in this paper outlines a theoretical framework that can be easily adjusted and employed for assessing the viability of ISM. This analysis highlights the role of the space economy in shaping future economic development and international collaboration, offering a reference source for policymakers, industry stakeholders, and academic researchers. An area for further studies would be the implementation of the model on a real case scenario, as this would help to understand and improve the robustness of the model.

However, it is essential to acknowledge the limitations of the models and results calculated. Currently, the model relies heavily on a simplified hypothetical scenario that lacks all the necessary elements of a real ISM. Additionally, the assumptions used may not entirely capture the total complexity and unpredictability of LEO space operations. These limitations can affect the accuracy of the projected economic outcomes, such as profitability timelines and return on investment.

Future work will focus on applying this model to a real-world scenario, which would provide valuable data to test the model's assumptions and refine its predictions. Implementing the model with actual project data will help to enhance its robustness and reliability. Additionally, work will be undertaken to increase the complexity and fidelity of the hypothetical scenario to explore the integration of more dynamic economic factors and market conditions that directly impact the ISM. This would involve adjusting the model to accommodate better variables such as fluctuating supply chain costs, technological advancements, and changing regulatory environments. By refining the model through empirical validation and broader variable integration, future research will provide more concrete guidance to stakeholders and contribute to a more informed decision-making process in the development of ISM ventures.

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