ASTRO-ECONOMICS: UNRAVELING THE FINANCIAL DIMENSIONS OF SPACE ENDEAVORS

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5 authors, including:

Bhushan Satish Deshmane
Indian Institute of Technology Kharagpur

Animesh Raj
Indian Institute of Technology Kharagpur

Annu Chaurasiya
Indian Institute of Technology Kharagpur

Dakshita Pokharna
Indian Institute of Technology Kharagpur

ASTRO-ECONOMICS: UNRAVELING THE FINANCIAL DIMENSIONS OF SPACE ENDEAVORS

BHUSHAN DESHMANE, ANIMESH RAJ, DAKSHITA POKHARNA, ANNU CHAURASIYA , HERAMB W.

ABSTRACT

Astro-economics, an emerging interdisciplinary field, examines the economic principles and implications of human activities in outer space. This literature review explores the evolution, current state, and future prospects of astro economics, highlighting key themes such as the commercialization of space, space tourism, resource utilization, and the economic impact of space policies. The review synthesizes findings from academic articles, industry reports, and policy papers, providing a comprehensive overview of how economic theories are applied to space-related activities. It identifies major stakeholders, including private companies, governmental agencies, and international organizations, and discusses their roles in shaping the economic landscape of space. Additionally, the review addresses the challenges of space debris, the viability of space mining, and the potential for sustainable economic growth through space exploration. By integrating economic models with space science, the field of astro economics offers valuable insights into the financial viability and strategic planning required for future space endeavors. This review concludes by outlining the critical areas for further research and the implications for policymakers and industry leaders aiming to navigate the complexities of the space economy.

Keywords – Astro-Economics; Space Policy; Space- economy; space-tourism.

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OVERVIEW

Our research paper on astro economics takes you on an exciting journey through the economic potential of space exploration. We uncover how celestial resources and space missions can revolutionize global markets and spark technological innovations. Dive into our analysis of market opportunities in space commercialization, and discover how investing in space can propel economic growth. We also tackle the regulatory, ethical, and sustainability challenges, offering insights and recommendations to guide the future of astro economic development. Join us as we explore the new frontier of economic opportunity beyond Earth.

1. Space activities and their economic calculations

1.1 Integrating sustainability in the design of space activities: development of eco-design tools for space projects

The integration of sustainability in space activities is becoming increasingly critical as humanity's presence in space expands. Space missions have traditionally focused on performance and reliability, often at the expense of environmental considerations. However, the growing awareness of ecological impact and the need to preserve both terrestrial and extraterrestrial environments have spurred the development of eco-design tools tailored for space projects. These tools aim to minimize the environmental footprint of space missions through innovative design strategies, resource-efficient processes, and sustainable materials. By incorporating sustainability from the inception of space projects, we can ensure that future space activities contribute positively to our quest for knowledge and exploration, while safeguarding the ecological balance of Earth and beyond.

1.1.1 Brief presentation of Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a powerful, internationally standardized method (ISO [1]) for evaluating the environmental performance of products, which include both goods and services. LCA assesses the environmental impacts of a product throughout its entire life cycle, from the extraction of raw materials to their disposal, known as the "cradle to grave" approach. In 2003, the European Integrated Product Policy [2] recognized LCA as the "best framework for assessing the potential environmental impacts of products."

Since then, LCA has been increasingly used in policy development and business. It involves comprehensive assessments of natural resource and energy consumption, as well as emissions to the environment (waste, air, water, and ground emissions) for each process in a product's life cycle. The first step is to inventory all incoming and outgoing flows of materials and energy for each life-cycle phase. The second step is to aggregate these flows to quantify various environmental impact indicators.

LCA is a multicriteria approach, addressing issues such as energy use, resource depletion, and pollution of air, soil, and water. It helps compare different scenarios and identify pollution transfers between different environmental impacts or life-cycle stages. This makes LCA useful for "design for the environment" approaches and as a decision-making support tool. Figure 1 illustrates the main principles and concepts of LCA.

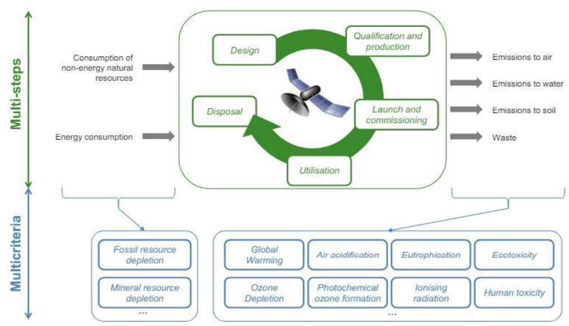

Figure 1: Illustration of the multi-step and multicriteria attributes of LCA

Figure - 1

[\Integrating sustainability in the design of space activities: development of eco-design tools for space projects Augustin Chanoine BIO by Deloitte Senior Manager 185 avenue Charles de Gaulle, 92200 Neuilly-sur-Seine, France achanoine@bio.deloitte.fr Yannick Le Guern (BIO by Deloitte), François Witte (BIO by Deloitte), Jakob Huesing (Rhea for European Space Agency), Tiago Soares (European Space Agency), Luisa Innocenti (European Space Agency)

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1.1.2 Data collection and data quality

An important data collection process helped gather environmental data for the entire life cycle of space missions:

- Knowledge about space missions and their design was collected by attending a CDF design session to understand the space mission design process.
- Extensive data collection was done with manufacturers of launchers and spacecraft.
- Over 10 experts were interviewed about different aspects, including:
  - Communication subsystem,
  - Thermal subsystem,
  - Solar arrays,
  - Batteries,
  - Chemical propulsion,
  - Electric propulsion,
  - Electronics,
  - Ground segment,
  - Testing activities.

More than 40 environmental Life Cycle Inventory datasets (LCIs) representing space activities were created during the project.

1.2 Eco Design of Space missions

Introduction:

Eco-design of space missions involves the systematic integration of environmental considerations into the planning, development, and execution phases of space projects. This approach seeks to reduce the ecological footprint of space missions through the adoption of sustainable materials, efficient resource utilization, and innovative design methodologies that minimize

waste and emissions. By embedding eco-design principles from the outset, space missions can enhance their environmental sustainability, in line with global initiatives aimed at environmental conservation. This strategy not only mitigates the environmental impact of space activities but also promotes technological innovation and operational efficiency, ultimately benefiting both space exploration and Earth's ecosystems.

1.2.1 Integrating environmental performance in the design of space missions

As a next step in the deployment of life cycle thinking for space applications and in order to foster the eco-design approach for space missions, ESA is currently establishing a common framework that can be used by any European stakeholder wishing to consider the environmental criterion when performing the design of a space project or to assess its environmental performance. This framework will include methodological and software tools, as well as an environmental database dedicated to space activities. Similarly to cost assessment, the environmental performance of systems is highly driven by design elements which are defined at an early stage in the design process [3]. Consequently, the eco-design approach should be initiated as early as possible in the design process (pre-phase A), when main design choices are still open, so as to maximize the potential for improvement of the environmental performance. However, as illustrated in Figure 2, environmental performance will also provide useful results throughout the mission's design process, as it will guide the design towards more Environmentally friendly technological/design alternatives at each step of the design process.

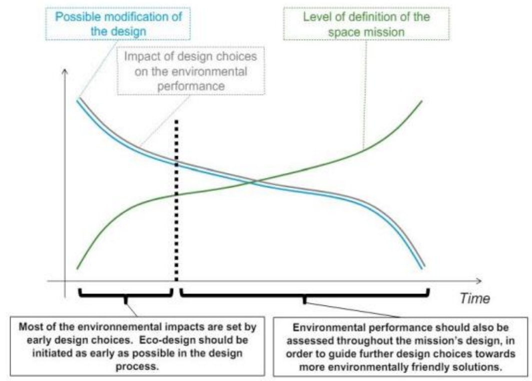

Figure 3: Eco-design in space missions' design process

Figure - 2

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1.2.2 Integrating environmental performance as a new design criterion for concurrent design

The European Space Agency (ESA) is integrating environmental performance into the early design stage of space missions, known as "pre-phase A." ESA, in collaboration with BIO by Deloitte, is developing a specialized eco-design software tool. This tool will assess the environmental impacts of a space mission design within the concurrent design approach. It will provide domain experts and system engineers with environmental performance data, serving as an additional decision-support element alongside technical performance, cost, planning, and risk considerations.

The first implementation of this eco-design software is taking place at ESA's Concurrent Design Facility (CDF). The software will be integrated with the CDF's design framework, the Open Concurrent Design Tool (OCDT), as shown in Figure 3. The eco-design tool includes a calculation module and a dedicated database with environmental information on typical materials, processes, and activities involved in the life cycle of a

space mission. This integration aims to enhance the sustainability of space missions by providing comprehensive environmental impact assessments during the design phase.

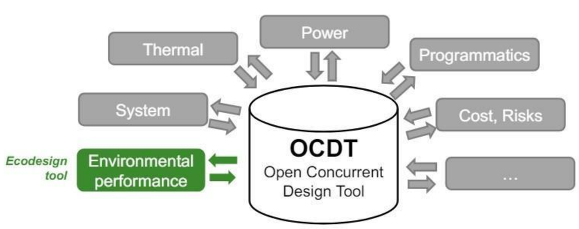

Figure 4: Integration of environmental performance as a new area of expertise at CDF

Figure - 3

[Integrating sustainability in the design of space activities: development of eco-design tools for space projects Augustin Chanoine BIO by Deloitte Senior Manager 185 avenue Charles de Gaulle, 92200 Neuilly-sur-Seine, France achanoine@bio.deloitte.fr Yannick Le Guern (BIO by Deloitte), François Witte (BIO by Deloitte), Jakob Huesing (Rhea for European Space Agency), Tiago Soares (European Space Agency), Luisa Innocenti (European Space Agency)

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1.2.3 Inputs of the eco-design tool

The eco-design tool requires mission-specific design data to assess the environmental impact of a space mission. These data describe various aspects of the mission under consideration. Some examples of the main types of design data used as input for the eco-design tool include:

1. Man-hours dedicated to mission design: This refers to the amount of time spent by personnel in designing the mission.

2. Bill of materials: This includes the type and mass of equipment or materials required for the mission.

3. Model philosophy: This indicates the number of full or partial models built during the design process.

4. Type, number, and duration of tests: This encompasses thermal vacuum, acoustic, or vibration tests, as well as the use of electrical ground support equipment, specifying their type, quantity, and duration.

5. Type of launcher: This identifies the specific launcher used for the mission, such as Ariane 5, Vega, or Soyuz.

6. Operation of ground stations and control centers: This includes the duration of utilization phases, the location of facilities, and the size of dedicated teams involved in

operating ground stations and control centers.

These inputs help the eco-design tool analyze and quantify the environmental impact of the space mission design, facilitating informed decision-making to optimize sustainability during the mission development process.

1.2.4 Outputs of the eco-design tool Multicriteria results

The primary output of the eco-design tool is the environmental performance of the analyzed mission for a specific design iteration. This performance is presented through a set of environmental indicators, each quantifying a specific environmental aspect. Additionally, the tool provides a breakdown of the contribution of each life-cycle step, helping to identify the main sources of environmental impact.

This breakdown can occur at various levels of the life cycle, including the mission level, specific life-cycle steps, or individual activities. By highlighting the main sources of environmental impact, this breakdown facilitates the eco-design process, allowing designers to focus on areas where improvements can be made to enhance the overall environmental performance of the mission.

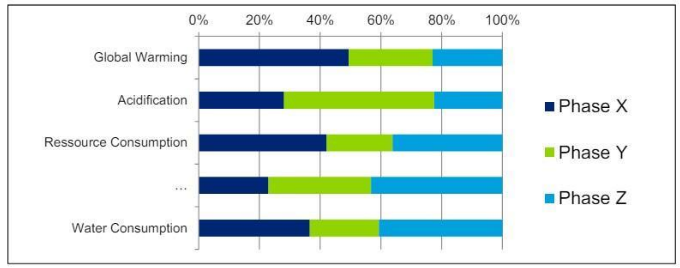

Figure 5: Breakdown of the impacts per life cycle steps (illustrative example)

Figure - 4

[\Integrating sustainability in the design of space activities: development of eco-design tools for space projects Augustin Chanoine BIO by Deloitte Senior Manager 185 avenue Charles de Gaulle, 92200 Neuilly-sur-Seine, France achanoine@bio.deloitte.fr Yannick Le Guern (BIO by Deloitte), François Witte (BIO by Deloitte), Jakob Huesing (Rhea for European Space Agency), Tiago Soares (European Space Agency), Luisa Innocenti (European Space Agency)

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1.3 Main Challenges

The initial Life Cycle Assessments (LCAs) for space missions were the first to cover the entire life cycle, revealing unknown environmental hotspots. To overcome this, an in-depth investigation of space mission life cycles was necessary. Given the complexity of these systems, an iterative approach was used for optimization. Data scarcity, especially for space-specific materials and processes, posed a challenge. Extensive data collection involved industry and ESA experts, supplemented by literature review.

The space sector's unique production chain, with minimal recurrent production compared to consumer goods, challenged common LCA assumptions. Tool development faced challenges such as populating the database with comprehensive and representative data. Collaboration with domain experts aided in data provision, validation, and defining technical options for various mission phases and subsystems.

Flexibility was crucial for the tool to accommodate diverse space mission configurations without requiring users to start from scratch. This ensured the tool's usability across a wide range of missions and equipment types.

2. Space Venture Europe: Entrepreneurship and Investment in the European Space Sector

2.1 The New Space Ecosystem

The investment of public funds in space exploration has led to the growth of a substantial and dynamic market for space-related services and products. These capabilities are increasingly acknowledged as essential tools for addressing a range of economic, societal, and environmental challenges. This has spurred the emergence of a disruptive commercially driven approach to space, characterized by ambitious initiatives and endeavors aimed at engaging in space markets with innovative schemes and business models.

In this evolving landscape, private entities have assumed a more prominent role, both in executing public programs and conducting independent space business activities. This reflects a growing recognition of the potential for commercial ventures to drive innovation and unlock new opportunities in space exploration and utilization. Consequently, the space industry is witnessing a surge in entrepreneurial activity, with private companies taking the lead in developing advanced technologies and pioneering new business ventures.

[source: https://www.liebertpub.com/doi/full/10.1089/space.2019.0020#body-ref-B1]

2.1.1 Emerging Trends in New Space Ventures: Attractiveness to Investors

This development, often referred to as New Space, features various interrelated trends described below:The evolution, commonly termed New Space, encompasses several interconnected trends. A prior study by the European Space Policy Institute (ESPI) [4] substantiated these trends, indicating a gradual shift towards a more business- and service-centric approach within the space sector. This transformation is distinguished by heightened investment and participation from private entities, including newcomers and startups.

Despite the yet-to-be-determined success and sustainability of the New Space model, new space ventures have garnered increased interest from specific investors. Financial markets perceive significant potential, with Bank of America Merrill Lynch estimating the space sector's value to potentially reach US$2.7 trillion within three decades [5]. Various factors are piquing financial markets' interest in the space sector, as illustrated in Figure 5.

Figure5

Space Ventures Europe 2018—Entrepreneurship and Private Investment in the European Space Sector

Authors: Sebastien Moranta sebastien.moranta@espi.or.at and Annalisa Donati

The evolution of New Space is propelled by several pivotal factors:

1. Entry of high-profile companies and entrepreneurs.

2. Strong innovation dynamics, introducing radically new concepts.

3. Reduced entry costs and accelerated time to market, facilitated by advancements in launch services, miniaturized systems, and Commercial Off-The-Shelf (COTS) technologies.

4. Cross-fertilization between space and ground technologies, including autonomous vehicles, 5G, Internet of Things (IoT) / Machine-to-Machine (M2M) networks, precision agriculture, and smart cities.

5. Increased penetration of space-based services and products, coupled with anticipated growth in demand.

Governments are increasingly recognizing the importance of fostering a more business-oriented leadership in the space sector. They are exploring new approaches to support the sector's economic growth and leverage the opportunities presented by this evolving dynamic for space programs.

2.1.2 Start-Ups Views on the European Space Entrepreneurial Ecosystem Overview of Survey Respondents

Out of the 64 start-ups surveyed, 56% were established in the last 5 years, and a total of 85% were less than 7 years old. The relatively small number of companies older than 7 years can be attributed to both the high failure rate of young businesses and the increasing number of new space ventures. Despite their average age, 55% of the surveyed companies are still in the early stage of development, with 12% at the seed stage and 43% at the start-up stage. Remarkably, 45% of these companies already declare themselves at growth, later, or steady stages of business development.

Regarding their origin, 55% of the start-ups were founded independently, while 35% emerged as spin-offs, including nine companies originating from the academic sector. The remaining 10% comprises ventures established following a company takeover and those created to run nonprofit associations. All respondents are Small and Medium Enterprises (SMEs), with the largest employing 78 workers, while 18% have no employees and rely solely on the founder(s). Only 14% of the companies have more than

20 employees, with the majority (38%) employing between 1 and 5 staff members. An overwhelming majority (84%) of these start-ups plan to recruit at least one additional employee within the next 12 months.

In terms of revenue, while a majority of European space start-ups generated income from their business activities over the last fiscal year, with 50% reporting revenue below €1,000,000 and 16% above, 34% of start-ups had no operating revenue yet. Consequently, a third of start-ups rely exclusively on financial support and seed investment to operate

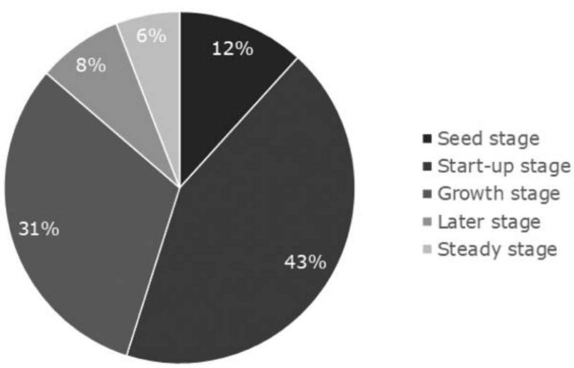

Figure 6

Space Ventures Europe 2018—Entrepreneurship and Private Investment in the European Space Sector

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The majority of respondents (68%) are located in five countries: the United Kingdom, the Netherlands, Germany, Italy, and France. However, it's important to note that the ESPI survey gathered information from start-ups in 16 different European countries. This distribution reflects the broader landscape of European activities in the space sector, encompassing both commercial and institutional endeavors. It mirrors the activities of national and supranational space agencies, as well as the outcomes of private investment databases

2.2 Perspectives on Space Start-Ups Business

Examining the core business activities [Fig. 8], 54% of surveyed firms operate in the upstream segment of the space value chain, while 32% focus on the downstream segment. Notably, nearly 40% of respondents are part of the Build segment, followed by downstream segments like Product and Analyze. Hardware production and engineering for the upstream segment remain prevalent among young space ventures.

Comparing the ESPI survey results with those of the ESM16 [6] , which covers all European start-ups, reveals that space start-ups are significantly more innovative and internationally oriented. Specifically:

- Space start-ups are largely innovation-driven, with 71% offering products that are global innovations, compared to 52% of all European start-ups achieving the same. Moreover, 60% utilize globally pioneering technologies, and 47% and 41% respectively implement innovative business models and industrial processes.

- In terms of global reach, 63% of space start-ups target the global market, with only 8% confined to their domestic market, whereas only 24% of all European start-ups offer solutions on global markets.

In terms of their business situation, respondents express a generally positive and optimistic outlook, with 75% assessing their company's current situation as satisfactory or good, and 82% anticipating even better prospects in the future [Fig. 7]. Additionally, half of the enterprises perceive their current condition as better than in the past. This optimistic stance on business development and growth aligns with the intentions of a vast majority of European space start-ups (84%) to recruit within the next 12 months.

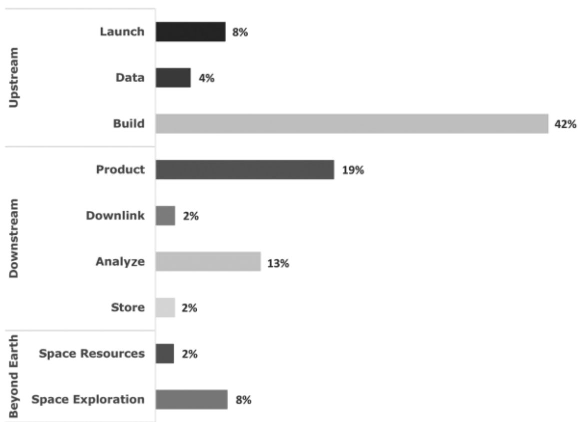

Figure - 7

Space Ventures Europe 2018—Entrepreneurship and Private Investment in the European Space Sector

Authors: Sebastien Moranta sebastien.moranta@espi.or.at and Annalisa Donati

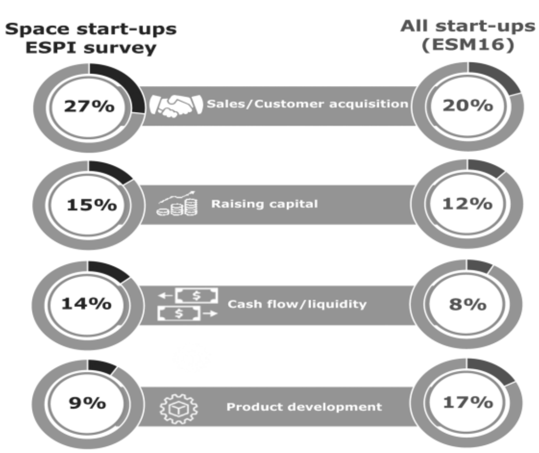

figure -8

Space Ventures Europe 2018—Entrepreneurship and Private Investment in the European Space Sector

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2.3 Insights into European Space Entrepreneurship

The study sheds light on the burgeoning landscape of private investment and entrepreneurship in Europe's space sector, signaling promising growth in new commercial space initiatives. However, a significant majority of space start-ups (78%) are still in pursuit of additional funding, relying on support from public entities.

Key Findings include-

1. Private investment in European space start-ups has seen a remarkable uptrend since 2014, reaching a remarkable pinnacle of €219.5 million in 2018.

2. Investment trends are notably concentrated, with a handful of large transactions dominating the landscape. In 2018, five deals exceeding €20 million collectively accounted for 64% of total investment.

3. The spirit of space entrepreneurship is notably vibrant across Europe, with investment deals surpassing €1 million recorded in 13 European countries. Particularly, the United Kingdom emerges as a notable success story in this realm.

4. The correlation between national public space budgets and domestic entrepreneurial activity remains nuanced, influenced by a myriad of factors including domestic ecosystems, policies, industry dynamics, and macroeconomic forces.

5. Investment inflow into the space sector is buoyed by synergies with other industries, especially evident in the downstream segment.

6. Typical European start-ups in the space sector are characterized by a modest team size of two to three founders, employing nine individuals, with plans to recruit an additional five in the coming year. Their annual revenue averages around €500,000.

7. Compared to their counterparts in other sectors, space start-ups exhibit a stronger focus on innovation and global markets, with 63% targeting international markets.

8. The space sector is perceived as fertile ground for entrepreneurship, offering ample opportunities for both innovation (62%) and commercialization (60%).

9. Despite acknowledging a challenging business environment, space start-ups remain optimistic about their growth prospects.

10. Space start-ups anticipate support, both financial and non-financial, from public sources.

11. Networking and mentorship are highly valued by space start-ups, suggesting potential benefits from dedicated events and programs.

12. Acquiring customers and securing sales pose significant challenges for space ventures, reflecting the formidable bargaining power of customers in the sector.

13. Space ventures call for greater government support, along with reductions in administrative burdens and taxes, to facilitate their growth and success.

3. SPACE Entrepreneurship

Space entrepreneurship represents a dynamic frontier in the modern era of space exploration, embodying the fusion of innovation, ambition, and commercialization in the cosmos. It encompasses the daring ventures of individuals and organizations aiming to unlock the vast potential of space for economic, scientific, and societal advancement. In recent years, the landscape of space entrepreneurship has witnessed a remarkable surge in activity, propelled by advancements in technology, evolving market dynamics, and a growing appetite for novel space-based solutions. From start-ups pioneering groundbreaking technologies to established companies venturing into new frontiers, space entrepreneurship is redefining the boundaries of what is possible beyond Earth's atmosphere. This burgeoning sector holds promise not only for revolutionizing space exploration and utilization but also for driving economic growth, fostering international collaboration, and addressing pressing global challenges. As humanity embarks on an exciting journey into the cosmos, space entrepreneurship emerges as a catalyst for innovation, exploration, and the realization of humanity's dreams among the stars.

3.1. Navigating Space Entrepreneurship

Space entrepreneurship is a significant topic of discussion in both European and United States space communities today. However, for some observers, the combination of space and entrepreneurial activities may not seem like a natural fit, especially in an industry that often favors large-scale projects led by governments or major multinational companies. The traditional space sector tends to view entrepreneurial endeavors with a mix of hope and interest in new approaches, alongside some skepticism and uncertainty about their potential impact.

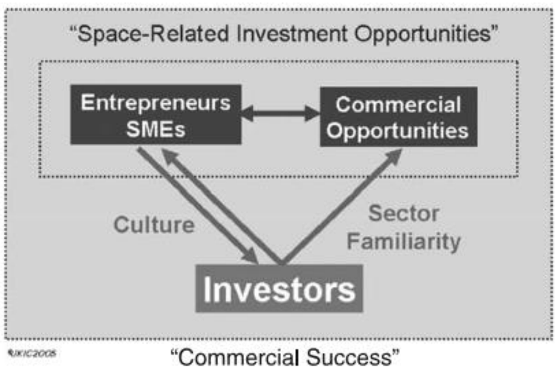


Figure - 9

Kreisel, J., Lee, B.H. (2008). Space entrepreneurship — Status & prospects. In: Schrogl, KU., Mathieu, C., Peter, N. (eds) Yearbook on Space Policy 2006/2007. The Yearbook on Space Policy, vol 1. Springer, Vienna. https://doi.org/10.1007/978-3-211-78923-0_12

While some space start-ups have achieved success in terms of market and financial performance, many have not yet made the transformative changes to the space industry and broader economy as anticipated. Nevertheless, over the years, a diverse array of commercial space activities has emerged, contributing significantly to the overall space business. Similar to the Information Technology sector, space entrepreneurs have demonstrated their ability to drive important technical innovations, cost efficiencies, and new business models. They excel in serving niche markets and often have faster time-to-market compared to traditional aerospace corporations.

It's essential to recognize that entrepreneurial space ventures are not isolated but rather interconnected with broader market trends and the availability of early-stage financing within the innovation ecosystem and policy framework. However,

It is taken into account and hence resulted,

despite their potential, space start-ups in both regions face significant challenges in securing financing due to a mismatch between investor expectations and the unique business models and risk profiles of space ventures.

3.1.1 Commercial opportunities in space?

Space business has evolved from its early non-commercial market foundations, dominated by government procurement, into a major commercial industry based on a mix of industrial and consumer markets. Driven largely by developments in space telecommunications, commercial space business today accounts for more than half of the space industry's consolidated global revenues. Given the complex market structures and financing mechanisms involved, however, it remains difficult to clearly distinguish between the major types of commercial space opportunities. The global space sector has been traditionally organized along technology and programmatic lines which, from a financial and commercialization perspective, is no longer an appropriate approach. Commercial space activities should instead be assessed in terms of the following generic characteristics and differentiators:

- Business nature and model
- Risks

3.1.2 Stakeholders Analysis in the Space Sector. A Deep Learning Value Flow Model Simulation. Antoni Perez-Poch

Stakeholder analysis has emerged as a crucial methodology for corporate analysis, yet its integration into large companies, especially public enterprises, presents significant challenges. Typically, requirements analysis, a widely adopted technique, prioritizes technical aspects over stakeholder considerations. The importance of stakeholder analysis is often overlooked until later stages of the design process.

However, space exploration, at its core, is a human endeavor driven by the innate curiosity to push boundaries and explore the unknown. Journalist Walter Cronkite famously dubbed the arrival of humans on the Moon as "the most important moment in human history" during the 2002 IAC Opening Ceremony. This underscores the profound impact of space exploration on humanity and emphasizes the need to prioritize stakeholder perspectives in corporate decision-making processes.

3.2 Space Sector Stakeholders

Stakeholders are defined as those individuals, entities or organizations that have a role in a definite process. The stakeholders' analysis is usually aimed at finding which the best organization design is that optimizes its effectiveness. The work is performed by focusing in the stakeholders that take a substantial role on the value chain of the company. Basic needs and identification of the main relationships are most relevant for the public sector, where the concept of 'added value' is more difficult to identify. If we would like to identify the key stakeholders at the space area, the question should be: Who are the stakeholders of space exploration that will make value grow? A review of the literature [7] [8] [9] [10] [11] will show us that the major characters had already been identified. Science, Security, International Partners, Economic Area, Executive & Congress, People,Educators and Media are the main groups of people and organizations that typically add value in the United States, according to the latter references. Some of them, like Educators and Media are mainly intermediaries with the People. Finally, the major public space agency in the US, NASA is noted, to which the private sector should be added in an emerging growing role. The recent appreciation of value co-creation lying multiple stakeholders has led to studies [12] that explore which motives and resources generate value in multinational case studies. In the building sector, for example, Herazo and Lizarralde [13] have studied different approaches to sustainability from the stakeholders' point of view. Exploration missions require that people involved in these areas make flow the benefit, tangible or intangible that emerges from the space activity. The overall process of identifying stakeholders and assigning them a proper role and interrelationships among the different systems involved, are known to be the design of the stakeholders model.

3.2.1 The Value Chain

The Value Chain as a vector to reingeneer the process Once the basic process of modeling is done, we will have a detailed map of the connections between the different stakeholders involved. The process model is a dynamic one, although only a steady-state photograph of the whole system is considered. At this point of time, we introduce the concept of value chain coming from the industry and information

systems architecture. Value chain is a collection of value flows which are connected by stakeholders, relevant to the

process. Major white papers and requirements standards [12] refer to these

concepts in the space area as well as others.

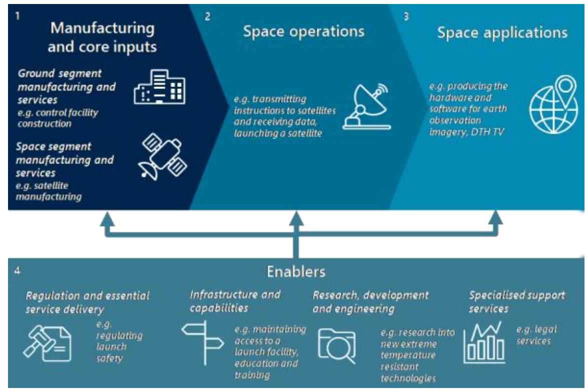
The chain has the responsibility to change and add a definite value onto the system. Only stakeholders that form part of input-output flows are the ones relevant to the reengineering process. By "Reengineering" we understand a major organizational change that aims to optimize the creation of value within the system. A reengineering process based on the value chain, should follow the next steps:

1- Defining value for our system

2-Modeling the stakeholders' matrix

3-Identifying the key stakeholders which contribute to the value chain, and

4-Rearranging the value flows in the organization to reinsert key stakeholders into the value chain



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[IAC-19-D5.2.5 Stakeholders Analysis in the Space Sector. A Deep Learning Value Flow Model Simulation. Antoni Perez-Poch Universitat Politècnica de Catalunya, UPC BarcelonaTech, EEBE Campus Diagonal-Besòs, C. E.Maristany 16, ES08019 Barcelona (Spain), antoni.perez-poch@upc.edu]

According to Cameron et al. [11], individual flows are categorized into six groups: Policy, Money, Workforce, Technology, Knowledge and Goods and Services. In the process of creating a value flow model framework, a number of decisions have to be made in order to simplify the value loops, and make the model easily understood. Value loops are defined as value chains that return to the starting stakeholder. Simplification of this map has no standard procedure, and

depends on the level of detail needed in the reengineering system.

3.2.2 Deep Learning Network Simulation

Deep Learning allows the computer to generalize input datasets without relying on a fixed governing law using highly complex forms of Artificial Neural Networks [14]. Feeding input datasets allow the computer to train relevant parameters to find the features common among the datasets. With enough input data, the machine learning algorithms are able to create accurate generalizations in a short amount of time, providing more accuracy than shallow neural networks like those explained in the previous section. 5.1. Convolutional Neural Networks Our Deep Learning Network (DLN) model is based on a Convolutional Neural Network (CNN). It was biologically inspired by the human visual cortex, where the cortical neurons partially overlap with each other to form receptive fields that cover the entire visual field. CNNs are usually applied in the area of image recognition, but can also be applied to other classification problems. The central idea of a convolutional neural network is to extract the pattern features of the input data. A crucial problem with the classic, fully-connected neural network is that it does not take the spatial position of the data into account. On the contrary, a convolutional neural network takes the position of the input data into account and runs multiple convolution and pooling operations before implementing the fully connected neural network on the data. Before the network is implemented to calculate the prediction, the weights and biases of the convolution layers, pooling layers and the fully connected layers are initialized between values of 0 to 1 in a Gaussian distribution. The input value flow structure image is fed into the convolutional neural network, and the convolution operation is applied to the input. The convolution layer of the network consists of multiple kernels. The presence of multiple filters allows the network to extract various features. After performing multiple convolution operations on the input, the dataset is reshaped to be fed into the neural network.

3.3 Conclusions

In our exploration of stakeholders' analysis, we have delved into its intricate connection with the value chain concept, juxtaposing it with the reengineering process as a potent driver of organizational transformation. This strategic realignment channels resources towards processes that augment overall system value, thereby fostering efficiency and competitiveness. Our inquiry extends to the integration of a more pronounced role for the private sector within space stakeholders' models, prompting us to meticulously assess the potential ramifications for operational efficacy.By quantifying the variables embedded within the value map, we unlock the capacity to deploy optimization methodologies, providing a tangible visualization of prospective alterations ensuing from heightened private sector engagement within the stakeholders' matrix. These sophisticated analytical tools afford us a glimpse into the future landscape of the space industry, offering insights into the dynamic interplay between various stakeholders and their impact on overarching goals and objectives.

4.Building an Economical and Sustainable Lunar Infrastructure to enable Human Lunar Missions

Introduction-

NASA has set its sights on an ambitious goal: to send the first woman and the next man to the surface of the Moon, with the lunar south pole identified as the primary target for this historic mission. This strategic decision stems from the recent revelation of significant lunar ice deposits within the permanently shadowed regions (PSRs) and their vicinity. This newfound understanding of the lunar south pole's potential as a repository of vital resources has propelled it to the forefront of NASA's lunar exploration agenda.

4.1 Lunar Infrastructure Systems for Sustained Human Presence on the Lunar Surface

This section delineates the infrastructure and surface systems imperative for establishing a long-term outpost to sustain human habitation on the lunar surface. Key assumptions underpinning this analysis encompass:

1) Leveraging International Space Station (ISS) subsystems as foundational elements for evaluation.

2) Envisaging a sustainable presence of six astronauts.

3) Contemplating mission durations extending up to 30 days.

4) Prioritizing the utilization of lunar resources to the greatest extent feasible, thereby mitigating the mass and cost associated with transporting cargo from Earth.

A new study was initiated to examine the feasibility of developing economical and sustainable lunar surface infrastructure capabilities and services in partnership with industry to meet the goals of NASA's Artemis program for a long-term, sustained human presence on the lunar surface by 2028. This work is an extension of the Lunar COTS concept [9,10] previously developed to leverage best practices from NASA's Commercial Orbital Transportation Services (COTS) program which introduced an innovative and economical approach for partnering with industry to develop commercial cargo transportation services to the ISS. [15] [16] [17] [18]

5.Powering the Moon: From Artemis Technology Demonstrations to a Lunar Economy

Powering the Moon is a critical aspect of NASA's Artemis program, which aims to establish a sustainable human presence on the lunar surface. This section explores the progression from initial technology demonstrations under Artemis to the development of a robust lunar economy. Central to this effort is the advancement of power generation and storage solutions capable of supporting prolonged operations in the Moon's harsh environment. These technologies will not only facilitate scientific research and human habitation but also pave the way for commercial activities and resource utilization on the Moon. By addressing the challenges of lunar power needs, NASA and its partners aim to create a foundation for a thriving lunar economy that can support future deep space exploration, including missions to Mars and beyond.

5.1 NASA's Vision for Lunar and Mars Exploration: Collaborative Efforts, Technological Advancements, and the Path to a Sustainable Lunar Economy

The National Aeronautics and Space Administration (NASA) has articulated a comprehensive long-term vision that includes the ambitious goal of sending humans to explore Mars. This vision is part of a broader strategy to extend human presence deeper into the solar system. As part of this overarching mission, there is a nearer-term objective focused on developing and demonstrating the new technologies, capabilities, and business models required for future human deep space exploration missions. [24][25][26][27][28][29][30][31][32][33][34]

5.1.1 Collaborative Efforts for Lunar Exploration :

Achieving these objectives necessitates robust collaborations with both commercial and international partners. These partnerships are critical for establishing the first long-term human presence on the Moon, which is seen as a stepping stone for further space exploration. Such collaborations will not only solidify American leadership on the lunar surface but also significantly enhance the United States' global economic impact.

By working with various stakeholders, NASA aims to leverage diverse expertise and resources, facilitating innovative solutions and cost-sharing in lunar exploration missions.

5.1.2. Expanding Lunar Surface Activities:

Interest in lunar surface activities is expanding beyond the scope of the current Artemis program. While Artemis primarily focuses on returning humans to the Moon and establishing a sustainable presence, there is increasing enthusiasm for additional surface activities and demonstrations. These include advanced manufacturing processes and agricultural experiments on the lunar surface. Such activities are crucial for developing the technologies and techniques needed for long-duration missions, both on the Moon and eventually on Mars.

5.1.3. Technological and Power Requirements :

To support these expanded activities, there will be a need for substantial advancements in power generation, reliability, and availability. The initial technology demonstrations focused on Mars will require scaling up to support larger and more complex operations. This includes addressing the challenges of providing sufficient power during the lunar night, which lasts approximately 14 Earth days. Solutions may involve advanced energy storage systems, enhanced solar power generation, and possibly nuclear power sources. Ensuring reliable power supply is critical for the success of both scientific experiments and human habitation.

5.2 Elements of NASA's Plan:

5.2.1- Advanced Power Systems:

Developing power systems that can operate efficiently in the harsh lunar environment is a priority. This includes creating solar power arrays that can withstand extreme temperature fluctuations and dust accumulation. Additionally, energy storage solutions such as batteries or regenerative fuel cells must be capable of sustaining operations during the prolonged lunar night. The integration of nuclear power systems, such as fission surface power units, is also being explored to provide a consistent and reliable energy source.

5.2.2- In-Situ Resource Utilization (ISRU):

Utilizing resources available on the Moon, such as regolith and ice, is essential for sustainable lunar operations. ISRU technologies aim to produce water, oxygen, and building materials from local resources, reducing the need for supplies from Earth. These technologies are critical for long-term human presence and for supporting missions to Mars and beyond.

5.2.3- Habitat and Life Support Systems:

Developing habitats that can protect astronauts from radiation, micrometeoroids, and extreme temperatures is crucial. These habitats must also provide life support systems that can recycle air and water, manage waste, and ensure a stable living environment. Advanced life support systems will be tested on the Moon to prepare for their use on Mars.

5.2.4- Scientific Research and Exploration:

The lunar surface offers unique opportunities for scientific research. This includes studying the Moon's geology, searching for water ice deposits, and conducting experiments in low gravity. These research activities will enhance our understanding of the Moon and provide valuable data for future Mars missions.

5.2.5- Commercial and International Partnerships:

NASA's approach includes fostering strong partnerships with commercial entities and international space agencies. These collaborations will enable shared use of infrastructure, such as lunar habitats and communication networks, and promote the development of a lunar economy. By working together, partners can achieve common goals more efficiently and cost-effectively.

Overall, NASA's vision for lunar and Mars exploration involves a multi-faceted approach that combines technological innovation, international cooperation, and commercial partnerships. By developing and demonstrating the necessary capabilities on the Moon, NASA aims to pave the way for sustainable human exploration of Mars and beyond. This ambitious endeavor will require significant advancements in power systems, resource utilization, habitat design, and scientific research, all of which will contribute to the long-term goal of extending human presence deeper into the solar system.

5.2.6. Conclusion

Selecting the appropriate microgrid architecture for lunar power distribution involves balancing mass, reliability, and complexity. The radial network is the most straightforward and lightweight but lacks redundancy. The ring network improves reliability with bidirectional power flow at the cost of increased mass. The mesh network provides the highest reliability with multiple redundant connections but is the most complex and massive option. The choice of microgrid architecture will depend on specific mission requirements, the criticality of uninterrupted power supply, and the acceptable trade-offs between mass and reliability for sustained lunar operations.

5.5. AC vs. DC for Power Transmission on the Lunar Surface

In this study, the power transmission system for the Artemis lunar microgrid is evaluated with a focus on AC versus DC transmission methods. The cables and all grid-to-load and grid-to-source converters are designed to handle a maximum power transmission capacity of 40 kW, which corresponds to the power capacity of the Fission Surface Power (FSP) plant. The layout of the Artemis electrical power assets is conceptual and subject to change, but for the purposes of this analysis, estimated line lengths for the cables are based on a notional layout.

The primary metric for comparing different design solutions is the total microgrid mass. This includes the mass of the cables and the converters used in each system design. Cables are assumed to be made from ETFE (ethylene tetrafluoroethylene copolymer) insulated twisted bundles laid directly on the lunar surface. The converters are bidirectional, capable of converting between DC-DC or AC-DC with efficiencies of 95% and 96.5% respectively. The mass of the cables includes both conductor and insulation materials, while the mass of the converters encompasses the enclosure, radiator, magnetic components, filters, and power electronic components. These values are derived from curve fits based on existing space power electronic systems.

5.5.1 AC vs. DC Transmission: Technical Considerations

1. Efficiency and Losses:

- **AC Transmission:** Typically, AC power transmission involves higher losses due to skin effect and reactive power components. In the context of the lunar microgrid, using AC would require careful consideration of these factors, as well as the additional mass and complexity of transformers and phase-shifting equipment necessary to manage these losses.

- **DC Transmission:** DC transmission, particularly at higher voltages, can be more efficient over long distances due to lower resistive losses and the absence of reactive power components. However, DC systems require converters to interface with AC systems and load points, which introduces complexity and potential points of failure.

2. Converter Efficiency:

- <u>DC-DC Converters</u>: For DC transmission, the study assumes the use of DC-DC converters with an efficiency of 95%. These converters are essential for stepping voltage levels up or down as required and for integrating with various system components.

- <u>AC-DC Converters</u>: In the case of AC transmission, AC-DC converters with a higher efficiency of 96.5% are used to convert the power for use by DC loads and storage systems. These converters need to manage harmonics and power quality issues inherent in AC systems.

3. Mass Considerations:

- The total mass of the microgrid is a critical factor, particularly in the context of space missions where every kilogram of mass is associated with significant launch costs and logistical challenges. The study calculates the mass of cables, which includes both the conductive material and the ETFE insulation. For converters, the mass calculations include the housing, cooling systems (radiators), magnetic components, filters, and power electronics.

- <u>Radial Architecture</u>: In this configuration, a single tie line is added between the two microgrids (specifically between the habitat and ISRU production areas). This addition provides a straightforward and lightweight solution but comes at the cost of lower reliability due to the lack of redundant pathways.

4. Material and Environmental Considerations:

- <u>Cables</u>: The choice of ETFE-insulated cables is driven by their durability and performance in extreme environments. ETFE offers excellent resistance to temperature variations, radiation, and mechanical wear, making it suitable for the harsh lunar environment.

- <u>Converters</u>: The design and selection of converters take into account the need for robust enclosures to protect against lunar dust, thermal management systems (radiators) to dissipate heat efficiently, and reliable magnetic and filter components to ensure stable power delivery.

5.5.2 Cost-Effectiveness Analysis of AC vs. DC Power Transmission on the Lunar Surface

The choice between AC and DC power transmission systems for the Artemis lunar microgrid must consider not only technical factors but also cost-effectiveness. While technical considerations such as efficiency, reliability, and mass are paramount, the financial implications of implementing each system are crucial for budgetary planning and resource allocation.

1. Initial Investment Costs:

- <u>DC Transmission</u>: DC transmission systems typically require fewer components compared to AC systems, potentially resulting in lower initial investment costs. However, the need for DC-DC converters and specialized equipment may offset these savings.

- <u>AC Transmission</u>: AC transmission systems may involve higher initial costs due to the complexity of transformers, phase-shifting equipment, and power factor correction devices. Additionally, the integration of AC-DC converters at load points adds to the overall system cost.

2. Operational Costs:

- DC Transmission: DC systems generally exhibit lower resistive losses over long distances compared to AC systems, potentially leading to reduced operational costs over the lifespan of the microgrid. However, the maintenance and replacement costs of DC-DC converters and associated equipment must be considered.

- AC Transmission: While AC transmission systems may incur higher resistive losses, the widespread availability of AC technology and components may result in lower operational costs over time. However, the complexity of AC systems can lead to increased maintenance requirements and higher operational expenditures.

3. Mass and Logistics Costs:

- DC Transmission: DC systems often feature simpler cable designs and may require less material for installation, leading to potential savings in mass and transportation costs. However, the additional mass of DC-DC converters and associated equipment must be factored into the overall mass budget.

- AC Transmission: AC systems typically involve more components and heavier infrastructure, resulting in higher mass and transportation costs. However, the availability of standardized AC equipment and components may streamline logistics and reduce procurement expenses.

4. Long-Term Viability:

- DC Transmission: The long-term viability of DC transmission systems depends on the reliability and performance of DC-DC converters and associated technologies. Investing in high-quality, durable components may mitigate the risk of premature failure and minimize lifecycle costs.

- AC Transmission: AC transmission systems benefit from established standards, interoperability, and a robust supply chain, enhancing their long-term viability and reducing the risk of obsolescence. However, ongoing technological advancements may necessitate periodic upgrades to maintain compatibility and performance.

5.5.3. Conclusion-

The decision between AC and DC power transmission for the Artemis lunar microgrid involves weighing technical, logistical, and cost factors. While DC offers efficiency advantages and simpler cable designs, AC systems integrate better with existing infrastructure. Choosing the microgrid architecture, like the radial layout, requires balancing mass and reliability. Cost-effectiveness is critical, demanding a thorough cost-benefit analysis to optimize resource allocation. Ultimately, the choice hinges on mission-specific needs, considering power demands, environmental factors, and logistical constraints. By carefully evaluating these aspects, NASA can select the most suitable solution to ensure the success of the Artemis mission and future lunar exploration endeavors.

6.Comparison of material sources and customer locations for commercial space resource utilization

The cost, mass and risk of human and robotic activities beyond Earth can be significantly reduced through space resource utilization (SRU) [ref]. SRU is the strategy of using natural resources from the Moon, Mars and other bodies .The use of SRU may also provide a means for commercial entities to earn revenue through space exploration by delivering resources. [38][39][40]

6.1 Methodology

6.1.1 Economic model

For each mission scenario, the minimum specific cost to acquire resources and deliver them to a customer location is calculated (in $ per kg of delivered resources). In order to do so, the total cost for the mission has to be calculated.Cost contributions that are included are for launch (Cl), development (Cdev), manufacturing (Cman), operations (Cop) and propellant (Cprop). It is assumed that the missions take place in a mid- to far-term time frame, which is reflected in the costs, i.e. it is assumed that technology has matured through intermediate missions and development and manufacturing costs are represented by aviation-like costs.

To compute the total cost, C, specific costs for the elements are multiplied by the total mass or time for that element:

$$C = Cl + (Cdev+Cman)mdry + Cop*tmis + Cprop*mprop$$

Finally, the specific cost, c (in $/kg), can be calculated using:

$$C = C/m_{r,sold}$$

in which $m_{r,sold}$ is the resource mass sold at the customer location (in kg).

6.1.2 Results

It can be noted however, that the costs presented in this paper will have significant uncertainty and risks are likely weighted strongly towards the increased costs. Dependency on intermediate missions advancing technology readiness and planning for the mid- to far-term time frame adds to the inherent uncertainties of cost estimation. Nonetheless, the results presented here can be used to focus future research on potentially more profitable and feasible missions.

6.1.3 Sensitivity analysis

This section presents a sensitivity analysis for a number of input parameters to the model. Because of the assumptions in the cost model and the inherent uncertainty of planning future missions, a sensitivity analysis is important.

6.1.4 Cost model assumptions

The methodology described in Method and Refs. [41], [42] assumes aviation-like costs for development and manufacturing costs elements. It is assumed that technology has matured sufficiently through intermediate missions, because of the mid-to far-term time frame considered for the missions.

7. An affordable lunar architecture emphasizing commercial and international partnering opportunities

7.1 Introduction

Since the cancellation of the Constellation Program, NASA officially has been focused on Mars as the next step for human exploration.

Often-cited reasons for this include: (1) should Nature prove to be favorable, the moon could be the basis for expanding the space economy through Off-Earth Mining (OEM) and other commercial endeavors; (2) the moon is scientifically interesting and could serve as a platform for scientific facilities; and (3) useful experience could be gained there for the human journey to Mars. [43][44][45][46]

7.2.1 On the Role of the Government Sector in the Architecture

For continued NASA investment in any future human exploration architecture, affordability is a political imperative. This translates into managing the magnitude of the public investment by NASA in lunar infrastructure while doing those things that governments can do to stimulate new economic opportunities there. The menu of such potential strategic investments include:

- Engaging in science and exploration (e.g., Lewis and Clark);
- Reducing economic risks and resolving some technical uncertainties to create tipping points and real options for space entrepreneurs;
- Performing R&D/DDT&E and first buys of basic systems/services.

7.2.2 Spreading the Costs

Development and production costs for each system are typically incurred over several years. The software tool we used to spread costs uses a 40/60 formula—that is, 40 percent of the cost is incurred by the mid-point of the development (or production) schedule. The remaining 60 percent of the cost is incurred during the last half of the scheduled duration.

7.3 Results

In order to assess affordability of any future human spaceflight architectures, it is essential to recognize that the budget for human exploration and operations supports important on-going programs. These include exploration systems development (SLS, Orion, and Ground Systems), Commercial Crew, and exploration R&D, as well as current ISS operations.

8. System analysis of an ISRU production plant: Extraction of metals and oxygen from lunar regolith

8.1 Introduction

The International Space Exploration Coordination Group (ISECG) identified three driving objectives for the development of ISRU technologies on the Moon: evaluating sustainable long-term human surface exploration, enabling the commercialization of cislunar space, and allowing the preparation for human Mars exploration. [47][48][49]

8.2 Objectives, requirements, and assumptions

The primary objective of this study was to analyze and compare the mass and power budgets of three different ISRU production plants that extract metals and oxygen from lunar regolith. Future work could expand the carbothermal reduction study for metal extraction, and include it into this mass and power budget comparison.

8.3 Mass, power, and sizing results

The goal of this study was not to provide an exact value of the payload mass that must be delivered to the lunar surface to establish a large-scale ISRU production plant, but rather to model different production plants with the same level of detail and under the same set of assumptions to allow a quantitative comparison between ISRU processes.

8.4 Economy of scale

ISRU production plants exhibit an economy of scale when they are capable of producing higher amounts of metals and oxygen more efficiently than lower production rates.

8.5 Conclusions

The results of this study and their further extensions aim to provide the starting point for further assessment of how in-situ produced metals and oxygen can lead to sustainable long-term human surface exploration.

9. The Federated Satellite Systems paradigm: Concept and business case evaluation

9.1 Introduction

This paper introduces and describes the FSS paradigm, and develops an approach integrating mission analysis and economic assessments to evaluate the feasibility of the business case of FSS. The approach is demonstrated on a case study on opportunities enabled by FSS to enhance space exploration programs sustainability, with particular reference to the International Space Station (ISS). [50][51][52][53]

9.2 Market assessment: distribution in earth orbit of potential FSS customers and suppliers

In order to understand the potential market achievable and the topology of the FSS network, we analyze the orbital distribution of spacecraft that could collaborate in a federation.The increasing data generation rates of new Earth Observation Satellites in LEO and their ground station access time constraints make them suitable candidates for engaging in a satellite federation.

9.3 Customers identification

First, potential customers of an ISS-based resource supply are identified among the active satellites surveyed in the market assessment .Representative customers range from LEO to GEO altitudes, with varying inclinations across mission categories to assess the sensitivity of the business proposition to varying orbital parameters. The next step, therefore, is to assess the accessibility of those customers from the ISS, where accessibility is defined by the combination of number of accesses, slant range, and access duration for each mission, for a given timeframe of interest.

9.4 Customer ranking

Accessibility i=∑j Duration/(MeanRange)^2

Ranking is required to prioritize customers and to define thresholds in selecting customers in the market. This step implements a ranking by considering both benefits and costs associated with customers, proposing an overall accessibility metric. Accessibility for customer *i* is defined as the sum of the ratios between time duration (i.e. benefit) and the square of slant range (i.e. cost) of each access:The accessibility metric defined in the above equation assumes that all customers are equally important. Moreover, it does not reflect the cost effects of requiring many handovers to achieve longer contact times. These assumptions are deemed acceptable in this preliminary analysis.

9.5 Supplier-side profitability analysis

A two-step approach is adopted for the assessment of the business proposition from a market perspective: first a cost analysis from the supplier perspective is conducted, estimating a financial break-even point and a selling price to the market. Successively, an analysis from a customer perspective is conducted, in order to verify that the set price point leads to a financial incentive to customers to adopt the service.The goal of the profitability analysis is to determine the marginal cost per equivalent transponder that allows the operator to break even from supplying FSS services, and to estimate the selling price to the market

9.6 Customer side opportunity cost analysis

Incentives to customers are represented by cost savings realized implementing a FSS hosted payload on their spacecraft. Cost savings are evaluated estimating the opportunity cost, which is done comparing the cost difference between FSS services and developing the system using business as usual practices

9.7 Conclusion

Space missions have been predominantly developed and operated as self-standing efforts.The paper provides formal definitions of the elements involved in satellite federations, providing a taxonomy that defines a whole range of options for spacecraft to be engaged in satellite federations.The paper then proposes an integrated approach to evaluate the business case of satellite federations dealing with intangible resources; the approach is demonstrated with the exploration of possible opportunities to enhance sustainability of human space exploration systems, such as the ISS.

10.Trades between opposition and conjunction class trajectories for early human missions to mars

10.1 Introduction

A Critical trade in the analysis of crewed deep space missions involves the investigation of the trajectories used for transit to Mars vicinity. There are two basic classes of trajectories that can be utilized for high-thrust, human exploration missions to Mars: conjunction-class and opposition-class. [54][55][56][57]

10.2 Considering Opposition

The objective of this study was to conduct a consistent comparative analysis of opposition and conjunction class Mars exploration missions to a level of detail requisite for a fair and credible assessment. Candidate missions were evaluated using common ground rules and assumptions and analyzed using a common set of tools. The study involved detailed assessments of mission trajectories and finely resolved evaluations of payload requirements, including propellant wet mass, propellant inert and dry masses, propulsive system mass, habitation sizing, and logistics and sparing requirements.

10.3 Risk Characterization

Before identifying the differences in risk between exploration trajectory cases, it is important to reiterate that the purpose of this analysis is to investigate opposition class missions as a viable alternative to conjunction class missions for initial human exploration of Mars space.In this study, there are two critical variations in mission constructs that drive risk: mission duration and transit path. Individual risks were identified based on these factors and comparatively evaluated between the conjunction and opposition class missions. When evaluating mission risk, it is important to distinguish between transit duration and total mission duration. Periods on Mars surface present different risks to the mission and the crew than the periods in space. The potentially large risks associated with long durations of Mars surface habitation will likely preclude long surface stays, requiring much of the crew period in Mars vicinity to be spent in orbit and thus much of the mission risks to be duration dependent. For this analysis, which concentrates on initial exploration missions, the evaluation of risk assumes orbital missions and/or short stays on the Mars surface.

10.4 Conclusions

By evaluating the risks associated with each mission concept, trades in mission reliability can be compared, particularly for initial missions. The long total durations of conjunction class missions can likely result in increased risk for early conjunction class missions due to risk sensitivity to mission duration.

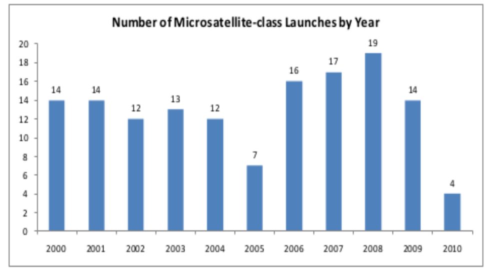

Fig 2. Historical Launch of Microsatellite-class Payloads by Year (2000-2010)

figure - 11

11. Market characterization

11.1 Introduction

The space industry is witnessing a significant transformation with the emergence of new market segments focusing on the launch of very-small and nano-sized payloads. These payloads, typically weighing less than 100 kilograms, are becoming increasingly important due to their diverse applications and cost-effectiveness. The 2010 Commercial Space Transportation Forecast by the U.S. Federal Aviation Administration (FAA) highlights this developing market. The introduction of competitively priced microsatellite launch vehicles is poised to shift payload launches from multi-manifest missions, where multiple satellites are launched together, to individual launches. This shift is expected to result in a higher frequency of launches, catering to the growing demand for small satellite deployment.[58]

Figure11 below shows the historical number of microsatellite-class launches per year.

11.2 Emerging Trends in the Launch of Nano to Very Small Payloads

According to the 2010 Commercial Space Transportation Forecast from the U.S. Federal Aviation Administration (FAA) Office of Commercial Space Transportation, there is a new market forming in space transportation. This market focuses on launching payloads that weigh less than 100 kilograms. The FAA report suggests that the rise of affordable microsatellite launch vehicles might lead to these small payloads being launched individually rather than together on larger rockets. This change could result in more frequent launches.

For instance, Rocket Lab, a private company, uses its Electron rocket to launch small satellites into space. This has allowed many new players, including universities and startups, to send their own satellites into orbit

11.3 Overview of Industry Structural Analysis

Industry Structural Analysis is a method used to understand how an industry works and the competitive forces at play. Created by Michael Porter, this analysis helps to identify the key forces that influence competition within an industry. The process involves several steps:

1. **Industry Definition**: Clearly define what the industry is about.

2. **Identification of Participants**: Identify all the players in the industry, including suppliers and buyers.

3. **Assessment Against the Five Forces**: Evaluate the industry using Porter's Five Forces model, which examines the power of suppliers, the power of buyers, the threat of new entrants, the threat of substitutes, and competitive rivalry.

4. **Determine Overall Industry Structure**: Understand the overall setup and dynamics of the industry.

5. **Analyze Trends**: Look at current trends and how they affect the industry.

6. **Identify Influential Aspects**: Determine which aspects of the industry can be influenced or changed to improve competitiveness.

Porter's analysis involves three steps: First, we define the industry. Second, we identify the key players, like the companies and organizations involved. Third, we analyze competitive forces, like the threat of new companies entering the market, the bargaining power of suppliers and customers, and the intensity of competition.

This gives us a clear understanding of the industry's dynamics.

Figure 1, below provides an overview of Porter's Five Forces that shape industry competition.[4]

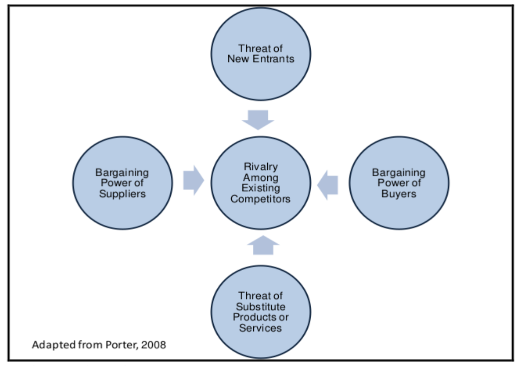

Fig.1 The Five Forces

Figure – 12

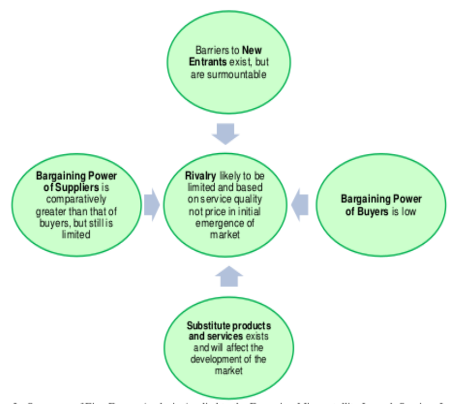

Figure 3: Summary of Five Forces Analysis Applied to the Emerging Microsatellite Launch Services Industry

Figure - 13

SpaceX is a great example. They developed reusable rockets, which significantly reduced launch costs, giving them an edge over competitors.

11.4 Conclusion

The market for launching very-small and nano-sized payloads is rapidly evolving, driven by technological advancements and the need for cost-effective space missions.

The FAA's forecast underscores the potential of this emerging market segment, highlighting the shift towards more frequent, individualized launches of small payloads. Understanding the structure of this industry through tools like Porter's Five Forces can help stakeholders navigate the competitive landscape and identify opportunities for growth and innovation. As the demand for small satellite deployment continues to rise, this market is set to play a crucial role in the future of space transportation.

12. Emerging Space Markets

12.1 Space Industry: General Trend

The space industry, like many others, experiences economic ups and downs. Historically, it has relied heavily on defense spending. For instance, the military buildup in the 1980s drove growth in aerospace and provided the technology for many space applications we see today. Much of the technology for major space products and services originally came from military projects.

This section focuses on "emerging" space markets. These are markets that aren't major economic players yet but have huge growth potential. They can create new economic activities, bring innovative products and services to the space market, and inject entrepreneurial energy. We will specifically look at four emerging markets: space tourism, on-orbit satellite servicing, microsatellite-based applications, and global navigation satellite systems. Each will be analyzed based on the technologies involved and the potential demand.

12.2 On-Orbit Satellite Servicing

Northrop Grumman's Mission Extension Vehicle (MEV) successfully docked with an Intelsat satellite to provide life-extension services. This mission showed that it's possible to service satellites in orbit.

Technical challenges include precise docking and ensuring operational safety, but advancements in robotics and autonomous systems are making these tasks more feasible.

In the future, we can expect more sophisticated servicing missions, including the construction of new satellites directly in space.

12.3 Microsatellites

Unlike large GEO satellites, microsatellites can operate in various orbital locations for a wide range of missions. Historically, microsatellites have been used mainly for scientific missions or as training platforms for new satellite industry entrants, with limited commercial applications so far.Microsatellites are not a well-defined service but are a reliable, low-cost platform customizable for many space missions using compact payloads. They use mostly space-proven off-the-shelf technologies, making their design and development manageable and costs relatively low. Their low mass further reduces costs due to cheaper launch opportunities. These factors lower the barriers to entry in this market, allowing many players to coexist.

Planet Labs operates a fleet of microsatellites that provide high-resolution images of the Earth's surface. These images are useful for applications ranging from agriculture to disaster response.

Despite their advantages, microsatellites face challenges such as a limited lifespan and the potential to contribute to space debris.The future looks promising with innovations in propulsion, miniaturization of components, and enhanced capabilities driving the growth of this market.

12.4 Global Navigation Satellite Systems

Among the emerging markets discussed, Global Navigation Satellite Systems (GNSS) are the most technologically and market-developed. The technical feasibility of GNSS was demonstrated over two decades ago with the launch of the U.S. Navstar satellites. Over the years, extensive military and civilian applications have been developed, but there is still significant growth potential in commercial applications.[59]

GNSS provides precise positioning and timing information critical for various applications, including navigation, telecommunications, and scientific research.The most developed systems include the U.S. GPS, Russia's GLONASS, Europe's Galileo, and China's BeiDou. Each system has its unique features and advantages.

Challenges include maintaining and upgrading these systems, but there's also significant potential for new commercial applications, such as autonomous vehicles and precision agriculture.Future advancements may include even greater accuracy, interoperability between systems, and the development of regional augmentation systems.

12.5 Conclusion

Predicting the future of the space market is challenging due to its complexity. It's too early to determine whether any of these emerging markets will become "the next big thing." Each market has a unique mix of technologies, potential applications, and sources of demand. While technical feasibility is necessary for success, economic feasibility is equally crucial. Without it, even the most promising technologies can fail commercially, as shown by the collapse of Iridium. Therefore, both technical and economic feasibility are essential for forming an emerging market. The success of each market depends on the harmonious co-evolution of technology and market. This coevolution can be illustrated by an "S-curve," a common tool in technology forecasting, showing the relative positions of the emerging markets discussed in their evolutionary trajectories.

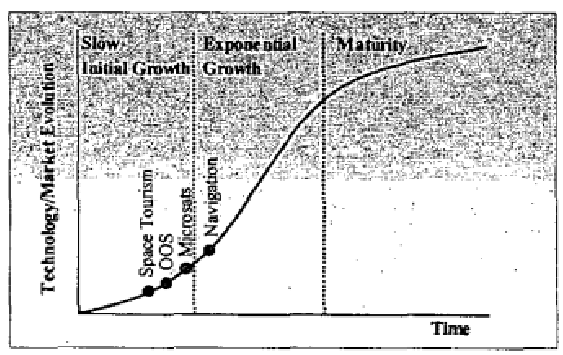

Figure 3: The co-evolution of technology and market

figure - 14

13. Analysis of Economic Dynamics in Astronomy

13.1 Introduction

Astro Economics is a new field that changes how we understand the economics of astronomical research. This section gives an overview of astro economics, tracing its development and importance in modern astronomy. It draws on important works and current research to explain how astro economic thought has evolved and its impact on astronomy [60].

This field helps us understand the costs, benefits, and efficient use of resources in space projects. It's crucial for managing the large investments required for space missions.

NASA’s investment in space exploration has led to not only scientific discoveries but also technological innovations that benefit other industries, like medical imaging and materials science.

13.2. Information Flow in Networked Telescopes

Networked telescopes are revolutionizing collaborative research by enabling easy data collection and sharing worldwide. This section explores how information flows within these telescope networks, detailing how raw data becomes useful insights. It covers data processing algorithms, data storage methods, and collaborative platforms, revealing the core functions of modern astronomical research networks [61].

Imagine a global team working on a shared online document, seamlessly contributing and improving it together. This is how networked telescopes work.

The Event Horizon Telescope (EHT), a global network of telescopes, produced the first-ever image of a black hole thanks to worldwide collaboration.

13.3. Cost Analysis and Organizational Dynamics

Understanding the economic landscape is crucial for managing astronomical research projects. This section provides a detailed cost analysis, examining the different cost factors involved in building, operating, and maintaining telescopes. Using mathematical models and real data, it explains the relationship between telescope size, funding levels, and knowledge production rates. It also looks at the organizational structures that support collaborative research, offering strategies to improve productivity and cost-efficiency [62].

Analyzing costs helps manage budgets and ensure financial sustainability, while understanding organizational dynamics helps streamline operations.

The James Webb Space Telescope project involved meticulous cost analysis and management to stay within budget while delivering a highly advanced scientific instrument.

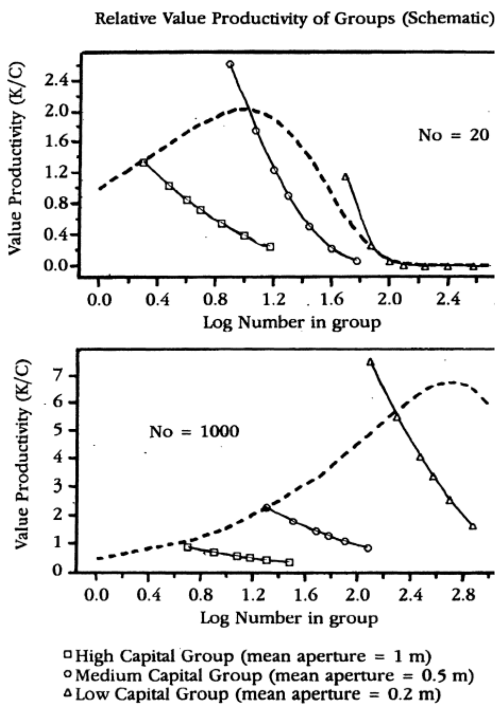

FIGURE 1. Relative new knowledge rates (dashed) and value productivi plotted against arbitrary ordinate scales are shown for two different cha organization scales and three capitalization levels.

Figure -15 [provided by NASA Astrophysics Data System]

13.4. Implications for Future Research and Collaboration

The findings from astro economic analysis have significant implications for the future of astronomical research. This section outlines potential research directions, such as developing new funding models and enhancing telescope networks with advanced technology. It emphasizes the importance of interdisciplinary collaboration and knowledge sharing to address the complex challenges in modern astronomy [63].

13.5. Conclusion

Astro Economics is a valuable tool for examining the economic foundations of astronomical research. By understanding costs, values, and organizational dynamics,

astro economic analysis helps make informed decisions and allocate resources effectively for scientific discovery. Future exploration of astroeconomics can open new frontiers in our understanding of the universe [64][65].

14. Space Tourism And It's Economics

14.1 Introduction

Throughout history, people have always been interested in exploring new and exciting places. Since the beginning of the space age, the idea of public space flights has been an unspoken goal for spacefaring nations. Space tourism aims to offer adventurous and recreational experiences in space. .Studies predict that in the coming decades, commercial space tourism will see a market revenue increase by about four times. This growth will expand the sector beyond suborbital flights to include orbital and deep space tourism.

14.2 Space Travel

14.2.1 History of Space Travel

Space travel has always fascinated people. The idea of space travel dates back to ancient times, with references to journeys to other worlds in Hindu myths. Today, space tourism is a dynamic activity with a broad scope due to four main factors:

1. It has its own purpose.

2. It helps achieve goals in other areas.

3. It supports other space activities.

4. It reflects society's adventurous spirit.

14.2.2 Modern Scenario of Space Travel

Space travel is becoming more accessible and appealing to a broader audience.

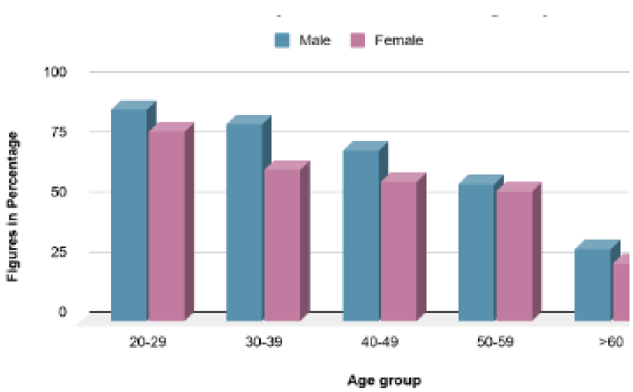

Figure 16 shows the demographics of interested candidates in space tourism by age group and gender in the USA..

14.3 Space Tourism

14.3.1 What is Space Tourism & Its Dawn

Space tourism is a commercial service provided by government-funded or private entities for customers to travel into space for leisure, business, or research purposes.

The suborbital market seems closest to unlocking the commercial potential of space tourism. Competitions like the X-Prize are pushing the boundaries to overcome the challenges of accessing space. If technical uncertainties can be resolved through successful suborbital launch demonstrations, more private investment in this area is expected. Regulatory hurdles can also be addressed as the space tourism market evolves. Experts believe that, in the

long run, an international framework for aerospace operations might develop, similar to Aviation Law and the Law of the Sea [66].

If reliable and relatively cost-effective means of accessing space are developed to

meet potential demand, space tourism could become a major growth driver for the space industry.

Space Tourism in the Context of a Diverse Market

In the early days of astronautics, space flight was predominantly a public pursuit, funded and managed by government agencies for strategic purposes. The realm of space tourism, once the domain of speculative fiction and government-led missions, has evolved into a dynamic sector brimming with economic potential and technological advancements. This section delves into the multifaceted aspects of space tourism, exploring its historical context, economic challenges, and technical requirements, while also elucidating the distinct dynamics of suborbital and orbital tourism markets. Generally, and notably in mainstream science fiction like the 1960s TV series "Star Trek," space flight was depicted as a government activity, with commercial and private endeavors scarcely mentioned [67].

14.3.2 The Importance of Public Access Space Flight

Historically, spaceflight was seen as a government enterprise, driven by national interests and funded by public money. The advent of space tourism has transformed this perception, ushering in an era whereprivate individuals can now journey to space. This shift highlights the growing significance of public access to spaceflight, contributing substantial revenue to the space infrastructure sector. Space tourism involves minimal payload investment, primarily utilizing existing infrastructure, with most revenue funneling back into the space infrastructure sector.

14.3.3 The Investment Trap

Olds et al. [68] examined various space tourism business models using a complex marketing tool called LMNoP, which included goal-seeking routines to assess business viability. The key issue identified was that while space tourism ventures could be profitable on a day-to-day basis, the initial investment costs were so high that they struggled to achieve overall profitability. Significant capital was tied up during the acquisition phase, and the generated revenue was insufficient to repay the start-up investment.

14.3.4 Launch System Requirements

The technical feasibility of launch systems capable of safely and efficiently transporting passengers is crucial for space tourism. The integration of personnel transport capabilities within reusable launch vehicles (RLVs) is a critical consideration, balancing additional costs with long-term economic viability. For example, adding personnel transport capabilities to the Skylon RLV would only increase acquisition costs by about 0.15%, approximately $20 million, which is negligible compared to the total development cost of around $10 billion. Developing a separate version of an RLV would be significantly more expensive, whereas a personnel module for Skylon would cost about $1 billion, compared to $8 billion for a new block of the RLV.

14.4 Types of Space Tourism

Space tourism has several sub-categories :

1. Sub-orbital tourism offers a compelling entry point into the space tourism market due to its lower development costs and greater accessibility compared to orbital tourism. Sub-orbital flights require significantly less speed and energy, resulting in lower weight ratios and thermal protection requirements. For instance, developing an operational sub-orbital vehicle for passenger use could cost between $100 million and $300 million, as estimated for SpaceShipOne by Scaled Composites [69]. Although the sub-orbital market is financially and technically more accessible, its value proposition is lower than that of orbital flights. Companies like Virgin Galactic have secured many deposits for suborbital flights priced in the $100,000s, whereas the sustainable market price for orbital flights is around $20 million per flight. Thus, while suborbital

tourism is easier to enter, it represents a lower value market.

2. Orbital tourism requires a more robust launch infrastructure, which can serve multiple markets beyond tourism. Previous reusable launch system proposals often justified their economic viability without considering space tourism. Integrating the development of orbital space tourism infrastructure with a general reusable launch infrastructure could help space tourism ventures avoid the investment trap by distributing costs across a broader market. This approach was deemed the most viable by Olds [70].

3. Tourism beyond Earth: Space Adventures Ltd. proposed lunar orbit trips for $100 million in 2007. SpaceX announced similar plans in 2017, with costs around $70 million using Starship. Investments from various industries and entrepreneurs indicate growing interest, expecting lower space travel costs and new tourism niches like Earth's orbit, deep space, and beyond.

14.5 Towards Affordable Orbital Space Tourism

14.5.1 Introduction

The allure of space tourism captivates both public and private sectors, with substantial interest among potential travelers. However, transitioning from concept to commercial viability is challenging, primarily due to the high costs of existing launch technologies. Market studies indicate a significant demand for space tourism, with many willing to spend considerable sums for a flight into space [71]. Space tourism may also drive the future of the launch industry, as the satellite launch market alone may not justify extensive investments in RLV development [72].

14.5.2 Existing Launch Vehicles: Economic Barriers to Space Tourism

Current launch vehicles pose significant economic barriers to space tourism. The Space Shuttle, for instance, could accommodate a passenger module for up to 72 tourists per flight, but at an estimated cost of $3.6 million per ticket [73]. Additionally, its turnaround time of approximately three months between flights makes it unsuitable for large-scale commercial operations (Koelle, 1997). Similarly, expendable launch vehicles like Soyuz are even more costly, with flights priced around $20 million, as seen in Dennis Tito's trip to the ISS (Naftel, 2000).

14.5.3 The Imperative of Reusable Launch Vehicles

The development of fully reusable launch vehicles is essential for sustainable and profitable orbital space tourism. However, achieving this goal is challenging, as evidenced by the high costs and eventual cancellations of projects like the X-33 and Kistler K-1 (Naftel, 2000; Salt, 1998). The X-33 program, for instance, accrued approximately $1.23 billion before its cancellation due to budget and schedule overruns (Naftel, 2000) [74].

14.5.4 Innovative Solutions and Collaborative Efforts

To overcome economic barriers, innovative approaches and collaborative efforts are necessary. Advancements in materials science, propulsion systems, and launch infrastructure could reduce costs and enhance the feasibility of commercial space travel. Strategic collaborations between government agencies, private enterprises, and international consortia are vital for pooling resources and expertise towards this shared goal.

14.5.5 Towards a Viable Future for Orbital Space Tourism

While the journey towards affordable orbital space tourism is fraught with challenges, the potential rewards are substantial. Achieving this vision requires concerted efforts and investments from diverse stakeholders. Overcoming technical, financial, and regulatory hurdles will be crucial in transforming space tourism from an aspiration into a tangible, sustainable industry with mass appeal.

14.6 Development Strategy in Reference to Air Tourism Businesses

14.6.1 Present Aviation and Space Tourism

Space tourism represents a growing sector with long-term prospects and commercial value. Companies are heavily investing in spacecraft and technology to promote space tourism, and governments are showing interest in this trend..

Space tourism targets a market beyond scientific research and manufacturing, appealing to the general public. Currently, suborbital tourism is nearing technical and financial feasibility, with companies securing many deposits for suborbital flights priced in the $100,000s range.

Market researchers predict that the space tourism market, valued at $435.1 million in 2018, will grow to $1,566.5 million by 2028.

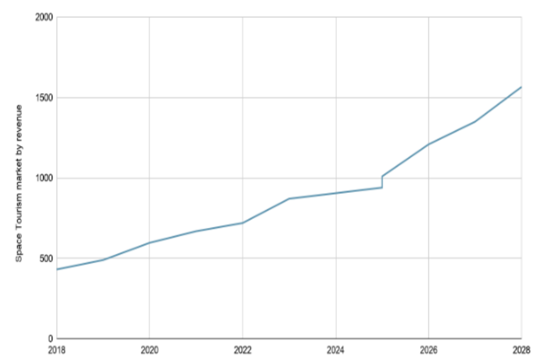

Figure 3. Shows a forecasted model for Space tourism market revenue ("Global Space Tourism Market...", 2020).

Figure - 17

14.6.2 Possible Future Development

Space tourism development can be likened to the aviation sector's early days. Initially, space tourism may resemble commercial aviation for luxury travel, with new spaceports developed. Future expansions might include orbital hotels and research stations, offering tourists varied experiences..

The potential growth of space tourism will likely follow these phases:

1. **Short-Term**: Suborbital flights providing brief weightless experiences.

2. **Mid-Term**: Regular orbital flights and stays at space hotels.

3. **Long-Term**: More affordable space travel options and destinations beyond Earth orbit.

14.7 Conclusion

The space tourism landscape is evolving, driven by technological advancements and market demand. The growth of this sector could lead to significant economic benefits, similar to the aviation industry's impact. Collaborative efforts, innovative business models, and regulatory frameworks will be essential in transforming space tourism from a niche market into a mainstream travel option.

The space tourism landscape is shaped by a complex interplay of economic, technological, and market factors. Sub-orbital tourism provides an accessible entry point, but integrating personnel transport within RLVs is essential for long-term sustainability. Moving forward, collaboration between public and private stakeholders and innovative business models will be crucial for realizing space tourism's full potential as a transformative sector of human exploration and economic activity.

15. Commercialisation of Space and Economics of Communication Satellites

15.1 Building blocks of a Robust Economy in Earth's orbit

15.1.1 Introduction :-

Economy is a term referring to the set of interrelated production and consumption activities relying on a careful management of available resources. The space resources upon which a robust economy in Earth's orbit can be created are: extremes in temperature, ultra-high vacuum, perpetually available solar power, reduced gravity, data, and remote sensing capabilities.

15.1.2 Challenges of Space Access and Utilization

Accessing and utilizing space is a complex and challenging endeavor, generally requiring an extensive infrastructure. This infrastructure is often described as a "three-legged stool," consisting of three critical components:

1. **Launch Systems**: The mechanisms and technologies required to send payloads into space.
2. **On-Orbit Processing**: The capabilities to process materials and conduct operations in space.

3. **Payload Return Capabilities**: The ability to bring materials and data back to Earth.

15.1.3 Commercial Orbital Transportation Service (COTS) Program

To that extent, a critical step forward and a major success so far has been the Commercial Orbital Transportation Service program, which has resulted in the privatization of what had previously been only government owned capabilities[75]. In addition, several New Space market segments [76] such as remote sensing, telecommunication, Earth Observation, navigation and small satellites have matured and become profitable market segments. Their success relied primarily on a much simplified infrastructure needed to generate, deliver and return the marketable product back to Earth, i.e. mostly data and imagery (communication, information). imagery, location In fact, most successful New Space market segments to date have been reliant only on one leg of the stool – launch systems.

15.1.4 Challenges in Payload Qualification and Return Capabilities

Despite these advancements, the process of qualifying a payload for launch and deployment on the International Space Station (ISS) remains cumbersome and slow. Moreover, there are currently no small sample return capabilities that meet the essential criteria for commercialization—frequent, affordable, and reliable. This gap highlights the need for further development in on-orbit processing and payload return capabilities to fully realize the potential of a space economy[77].

15.1.5 Aligning Technological Innovation with Market Demand

Commercializing a technology, or "taking a technology to market," relies on the alignment between three critical components: technological push, business development, and market and economic pull. This alignment ensures that innovative technologies not only reach the market but also meet the needs and demands of consumers, creating a sustainable and profitable business model. This review explores the strategies and best practices for achieving this alignment, examining the roles of technology development, business strategies, and market analysis in successful technology commercialization.

15.1.6 Commercialisation of Space

15.1.6.1 Lessons from NASA's Space Product Development Program: Strategies for Cost-Effective Commercialization in Space

Workshops targeting commercial business opportunities for space or microgravity utilization were organized by TRW Aerospace (Purchased in 2002 by Northrop Grumman) in the 1982-1983 timeframe as part of the Space Station Needs, Attributes and Architectural Options study for NASA.

In 1986, NASA created the Space Product Development Program (SPDP) managed out of NASA Marshall Space Flight Center in Huntsville, Alabama [78] This program was terminated around 2006, concurrently with the NASA microgravity science program, to redirect these resources to implement the "Vision for Space Exploration."[79] During its ~20 years of operation, the SPDP set in place 17 NASA Commercial Space Centers

(CSC) through cooperative agreements and focused on helping the industry design and fly experiments in space [80]. Out of these 17, 11 CSC's were directly managed through the program and 6 provided business assistance.

The budget per year per center was about $1M and their whole operation was considered extremely cost effective (about 30% of NASA space research projects were developed by these centers although they received only ~5% of the total research budget during that time). Several components that helped with the cost efficiency have been identified[81]:

1. Standardization & miniaturization of research hardware;

2. Open source facility models to tap the creativity of everyone;

3. Obsession with customer satisfaction;

4. Self-sponsored industry participation sought out and encouraged;

5. Supporting funds to small university groups to provide the know-how and industry interface;

6. Co-sponsored (government and industry) hardware development at the CSC;

7. Efficient process for flight safety reviews at JSC;

8. Small business-like organizational structure: problem solving and accomplishment of goals relied on the continuous free-flow of information within the team instead of a thigh, formal management structure;

9. Small solution focused teams.

15.1.6.2 Balancing out Risks and Investments

About a decade later (1997), the Potomac Institute for Policy Studies issued a report on the commercialization of ISS[82] summarizing insights from more than two hundred people representing approximately 50 companies, universities and government agencies. The study addressed three areas and provided findings and recommendations, selectively summarized below:

1) Commercialization of human orbital space flight is beneficial to the nation through:

a) Enhancing US industry competitiveness and national prestige. Orbital space it is recognized as "the latest in a number of frontiers". Federal government has been critical in the past in fostering commercialization to develop waterways, highways, railways and airways and it should in a similar manner foster orbital space flight.

b) Maintaining the NASA technology transfer program as an important asset since it has generated a myriad of spin-offs of new technologies to non space industries and acted as a bridge for private sector involvement.

c) Privatizing space assets; thereby increasing availability and quality while reducing cost. "It costs the government up to three times as much to develop and fabricate equipment through conventional contracts as it does by allowing the private sector to accomplish the same job, using performance specifications and best business practices."

d) Allowing NASA to focus on new frontiers. "These challenges will be easier to pursue if orbital space is 'normalized' by commerce."

2). There are interesting, plausible and viable areas for commercial ventures and also major challenges that must be overcome. "Both biomedical and material research provide important insight into earth-based processes (macromolecular crystallography investigations, microencapsulation systems, gallium arsenide thin film, etc.)". Of concern is the "dependency on the consistency of government policy for space access, impediments to space access, lack of transparency to the business community, diminishing efforts within NASA to foster commercialization, lack of fulfillment of policies and promises and procurement and procedural inflexibilities."

3). The government role in fostering commercialization is primarily through pump-priming to encourage and ensure successful commercialization as measured by "the extent to which industry has assumed responsibilities, funding and conduct of orbital space flight ventures and the extent to which government's role declines.

Successive administrations mandated a strong commercialization role to NASA, and NASA itself recognized that "commercialization of technology is comparable in importance to and an integral part of its aeronautics and space missions"25. Several recommendations from this study remain to be (re)considered with open minds and embraced with open hearts:

a).Establish a solid budget for commercialization and an institutional center within NASA to accommodate commercial participants;

b). Begin an outreach program to help industry learn how to do business with NASA;

c). Represent the private sector in formulating plans, strategies and policies;

4). Develop incentives for NASA management and personnel to foster commercialization goals and discourage in-house competition with private sector;

5). Coordinate commercial activities with other government agencies;

6). Accept the role of Anchor Tenant where plausible;

7). Recommend tax incentives to Congress.

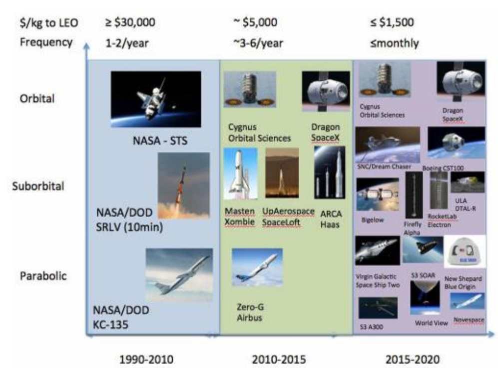

Figure 8: A major limitation to date in taking full advantage of the microgravity and space environment has been the extremely high price of launch costs (usually referenced as $/kg to Low Earth Orbit, LEO). The microgravity environment is accessible for various durations through parabolic (~20 sec), suborbital (3-5 min) and orbital (days, months, years) flights. Over the past two decades, the commercialization and diversification of space infrastructure has resulted in a significant increase of flight frequency as well as lowering of the price per pound to orbit. To note that numbers cited here for $/kg to LEO are first order estimates for the purpose of highlighting the current trend.

Figure - 18

15.1.6.3 Recent Trends

The cost of space transportation has traditionally been very high and, in general, viewed as one of the biggest obstacles to space commercialization [83][84][85].

ULA quotes an average mission price of $225M for all Atlas and Delta launch services (for a performance ranging between 10,000 kg for Atlas V 401 to 28,370 kg for Delta IV Heavy) [93]. SpaceX currently sells off-the-shelf Falcon9 launches for $61.2M [94] for a total performance of 13,150 kg [86]. Elon Musk, owner and CEO of SpaceX, indicated at the National Press Club [87] that the cost of propellant is only 0.3% the cost of the rocket (this yields about $200,000 for a $60M launch) and that the first stage cost is approximately "less than three-quarters" of the cost of the entire rocket. If full reusability of Falcon 9 (both first and second stage) could be achieved, the total price of the launch would go down about one order of magnitude. While full reusability is very difficult to achieve (although not impossible), even with partial reusability prices would go down and the quantity produced would go up through economies of scale. The recent successes of return to launch point (the first step towards reusability) of Blue Origin's Sheppard vehicle (suborbital) and SpaceX's Falcon 9 First stage (orbital) are historical turning points opening up truly innovative opportunities to the US and world private sector.

Total private dollars investments in space have also been on the rise with 1995-2002 annual totals (except 1998) being around $2.5 million dollars with a significant increase towards the $2.5 billions in 2015.

15.1.7 The Role of Orbital Solar-Powered Data Centers and Orbital Currency in Shaping the Low Earth Orbit Economy

The orbital currency, obtained through "mining" operations performed on orbital solar powered data centers, will directly connect the resources of space utilized in running and operating these data centers (space solar power, vacuum, cold of space) to create meaningful economic valuable currencies. Such currency may be key to enable future marketplace operations in earth's orbit, orbit to earth transactions as well as orbital and beyond orbital economy. The concept of orbital solar powered data centers/orbital data farms together with the orbital currency (technology disclosure) that emerges out of it [88], is central to the development of a robust economy in Low Earth Orbit as well as supporting NASA's future deep space exploration missions. The concept relies on using solar power resources as well as orbital computers or supercomputers to provide data analysis on orbit and enable more optimized, efficient downlink to Earth of pre-processed information as well as other locations in the solar system and beyond (Moon, Mars, etc.).

To ensure a successful commercialization of Low Earth orbit and the creation of an orbital economy, the central idea should build upon setting in place successful partnerships around shared value creation [98].

Coupled with a systematic and strategic step by step approach (LEO economy, LEO infrastructure for exploration of cis-lunar space, the moon and beyond, cis-lunar economy, lunar infrastructure, etc.) in which something robust is set in place including a smooth transition of ownership and resources from government to commercial before expanding to the next step, has the potential to result in a sustainable and successful space exploration program[89].

15.2 Enhancing the economics of communication satellites via orbital reconfigurations and staged deployment

15.2.1 Economic Advantages of Staged Deployment Strategy in Space Infrastructure

The staged deployment strategy is designed to minimize initial deployment costs by implementing an affordable system initially, with the option to expand in stages. This approach has significant economic implications, particularly in the context of space infrastructure and technology deployment. The following sections outline the key economic benefits and considerations of the staged deployment strategy.

15.2.2 Economic Benefits of Staged Deployment

15.2.2.1. Spreading Expenditures Over Time

The staged deployment strategy spreads expenditures over time, which reduces the financial burden associated with the initial deployment. By deploying additional stages only when necessary, this approach allows for a more manageable allocation of resources.

The present value (PV) of the cost for deploying a new stage can be calculated using the formula:

$$PV(Q) = Q/(1+r)^t$$

Where:

- r is the discount rate,
- Q is the cost for deploying a new stage,
- t is the number of years between the initial deployment of the system and the deployment of the new stage.

As t increases, the present value of the cost Q decreases, making future expenditures more financially manageable. This temporal distribution of costs is a primary economic advantage of the staged deployment strategy.

15.2.2.2. Adaptability to Market Conditions

Another significant advantage of the staged deployment strategy is its flexibility in responding to market conditions. This adaptability ensures that additional capacity is only deployed when market demand justifies the expenditure. If market conditions are unfavorable, further deployment can be delayed, keeping expenditures low and mitigating economic risks.

- **Market-Driven Expansion:** If demand is high and revenues are sufficient, additional stages can be deployed to increase capacity.
- **Economic Risk Reduction:** By aligning deployment stages with market conditions, the strategy minimizes the risk of economic failure. This prudent approach ensures that investments are made only when they can be justified by market conditions and financial performance.

15.2.3 Economic Considerations in Satellite Life Cycle Costs

Understanding the life cycle costs of satellite constellations is crucial for planning and managing space missions. For a flexible system, three types of expenditures are identified:

1. **Initial Development Costs (IDC)**: These costs correspond to the price of deploying the first constellation in the path. They do not include the price of real options, which are neglected up to this point.
2. **Operations and Maintenance Costs (OM)**: These costs capture the operational expenses of a deployed constellation, including orbital maintenance, servicing of ground stations, and replenishment of failed satellites.
3. **Evolution Costs (ΔC)**: These costs correspond to the necessary investments to deploy the next stage of the path. For example, in the case of Low Earth Orbit (LEO) constellations, deploying a new stage involves the manufacture and launch of new satellites.

A case study on the economic value of staged deployment for LEO constellations of communications satellites revealed that this strategy could lower the life cycle costs of Iridium-like systems by more than 20%. This reduction is achieved by spreading the cost of adding more capacity over time and providing system managers the flexibility to adapt system capacity to the unfolding market demand.

15.2.4 Conclusion

The staged deployment strategy provides a balanced approach to deploying space infrastructure by spreading expenditures over time and adapting to market conditions. This method reduces economic risks and allows for more flexible and sustainable financial planning. By carefully considering transition costs and the impact of discount rates, the staged deployment strategy can significantly enhance the economic viability of large-scale space projects.

16. The Economics of Space debris in perspective

16.1 Space Debris: Challenges and Economic Impact

16.1.1 Introduction :

Space debris, also known as space junk, is an increasing concern for space missions and commercial operations. The accumulation of debris in Earth's orbit poses significant risks to active satellites and spacecraft, and managing these risks incurs substantial costs. This review examines the current state of space debris, its economic implications, and the impact on commercial space activities.

16.1.2 Current State of Space Debris

1. **Quantification of Space Debris:**

- The US Air Force Space Surveillance Network tracks over 20,000 objects larger than 10 cm.
- The European Space Agency (ESA) estimates the total amount of untracked debris (measuring between 10 cm and 1 mm) to be almost 129 million [90].
- This vast number of debris pieces increases the likelihood of collisions, which can generate even more debris and threaten operational satellites and future missions.

2. **Economic Costs of Managing Space Debris:**

- Costs associated with managing space debris are rising, reflecting the increasing complexity and risk of space operations.
- Protective and debris mitigation measures, such as shielding, manoeuvres, and relocating satellites to graveyard orbits, can constitute 5-10% of total mission costs for operators in geostationary orbit. Given that mission costs often run into hundreds of millions of US dollars, these measures represent a significant financial burden [91].
- **Type of Cost and it's description**

Type of cost/impact	**Description**
Satellite and constellation design	Costs associated with satellite shielding, collision avoidance capabilities, safehold modes and redundancies (i.e. launch extra satellites as spares). Satellite constellations increasingly include spares for system resilience, but this solution often becomes part of the problem.
Debris-related damage	Loss of functionality or loss of entire satellites. Many incidents go unreported
Operations costs	Costs of space situational awareness (SSA) activities, services and software. Data blackouts when conducting avoidance manoeuvres.
Orbit clearance costs	In the geostationary orbit: Relatively low, equivalent to about three months of station keeping. In the low-earth orbit above 650 km altitude: Very high and requiring specific satellite subsystems (on-board computer).
Insurance costs	Overall, limited use of in-orbit insurance by operators for space debris. Space debris collisions have historically been considered low-probability and not affecting insurance premiums.

Table 1 : Current Economic Impact of space debris [92]

***Insurance costs:** it is estimated that only six percent of satellites in low-earth orbit have in-orbit insurance, compared to nearly half of all GEO satellites [93], [94].*

Type of cost/impact	**Description**
Loss of unique applications	Space observations from some of the orbits most vulnerable to space debris are often the best or the only source of data and signals in their domain.
Lives lost	The International Space Station is located at about 400 km altitude. A Chinese Space Station at a similar altitude is under preparation.
Interrupted time series for earth science and climate research	Uninterrupted time series are crucial for the accuracy and reliability of weather prediction and climate models.
Curbed economic growth in the sector	Many future LEO communication services would be affected, on orbit and/or during orbit-raising, as several planned constellations are located near or above the thickest LEO debris belts.
Reduced access to finance	Reduced access to venture finance, with investors preferring more affordable and less risky terrestrial alternatives.
Distributional effects	The loss or perturbation of certain low-earth orbits could be felt more heavily in rural low density residential areas and low-income countries

Table 2: Potential future impacts of space debris [95]

16.1.3 Challenges and Demerits of Space Debris

Space debris presents several significant challenges and demerits:

1. **Increased Collision Risk**: As the number of objects in orbit grows, the likelihood of collisions between satellites and debris increases. This can lead to the destruction of

operational satellites, causing loss of services and financial investments.

2. **Creation of More Debris**: Collisions and explosions in space create more debris, which can lead to a cascading effect known as the Kessler Syndrome. This phenomenon results in an exponential increase in debris, further escalating the collision risk and making space operations increasingly hazardous.

3. **Threat to Astronaut Safety**: Space debris poses a significant danger to manned space missions. High-velocity debris can damage or penetrate spacecraft, endangering the lives of astronauts aboard the International Space Station (ISS) and other manned missions.

4. **Cost of Mitigation and Avoidance**: Space agencies and companies must invest in technologies and strategies to avoid collisions, such as satellite shielding, debris tracking systems, and collision avoidance maneuvers. These measures add to the operational costs of space missions.

5. **Impact on Space-Based Services**: Disruptions caused by space debris can affect various space-based services, including telecommunications, weather forecasting, navigation, and Earth observation. This can have widespread economic and societal impacts.

6. **Environmental Impact**: The proliferation of space debris also has potential long-term environmental impacts on the near-Earth space environment. Increased debris can make certain orbits unusable, limiting future access to space and hindering scientific and commercial activities.

7. **Regulatory and Liability Issues**: The international community faces challenges in regulating space activities and assigning liability for debris creation. The lack of comprehensive legal frameworks complicates efforts to manage and mitigate space debris effectively.

8. **Technological Limitations**: Current technologies for tracking, monitoring, and removing space debris are still in development and face significant technical and financial challenges. Effective debris removal solutions are not yet fully operational, limiting immediate mitigation efforts.

16.1.4 Impact on Economic Growth in the Space Sector

1.Current Commercial Operations

- Most commercial satellites, primarily for Earth observation and telecommunications, operate at altitudes between 400-700 km [96].

- The value of commercial operations in low-earth orbit (LEO) is currently lower than that of telecommunications activities in geostationary orbit (GEO). However, LEO operations are expected to grow significantly due to the demand for satellite broadband.

1. **Future Prospects for Satellite Broadband:**

- Satellite broadband is considered a key driver of future space activities and revenues.
- Despite uncertainties regarding business models and viability, the expansion of satellite broadband services is anticipated to boost economic growth in the space sector, particularly in LEO.

16.2 Mitigation Strategies and Policy Considerations

1. **Technological Solutions:**
    - Innovations in debris tracking and collision avoidance technologies are crucial for improving the safety and sustainability of space operations.
    - Development of active debris removal (ADR) technologies could play a significant role in reducing the amount of space debris.
2. **Regulatory and Policy Frameworks:**
    - International cooperation and regulatory frameworks are essential to address the space debris issue effectively.
    - Policies promoting responsible behavior in space, including guidelines for end-of-life disposal and debris mitigation practices, are necessary to ensure the long-term sustainability of space activities.

16.3 Conclusion

The management of space debris is a critical challenge that impacts the safety and economic viability of space operations. As the space sector continues to grow, particularly with the anticipated expansion of satellite broadband services, addressing the space debris issue will be essential to sustaining economic growth and ensuring the safety of space missions. Continued investment in technological solutions and the development of robust regulatory frameworks are imperative to mitigate the risks posed by space debris and support the future of commercial space activities.

Consensus Summary

This literature review on astro-economics has explored the multifaceted economic principles and implications of human activities in outer space, drawing from an extensive array of academic articles, industry reports, and policy papers. Our analysis covered key themes such as the commercialization of space, space tourism, resource utilization, and the economic impact of space policies.

One of the central findings is the significant role of private companies and governmental agencies in driving the space economy forward. The increasing involvement of private enterprises has led to remarkable advancements in technology and cost reductions, making space more accessible. The commercialization of space, particularly through ventures like space tourism and satellite deployment, presents substantial economic opportunities and challenges. The development of eco-design tools and sustainability practices in space activities has been emphasized as crucial for long-term economic viability and environmental stewardship.

Our review also highlighted the importance of resource utilization, particularly the potential of lunar and asteroid mining. These activities promise to revolutionize the space economy by providing essential materials for further space exploration and supporting sustainable human presence beyond Earth. However, these opportunities come with significant challenges, including technological, regulatory, and environmental considerations.

The economic implications of space policies were another critical area of focus. Effective policies and international collaborations are essential for addressing issues such as space debris, ensuring fair access to space resources, and fostering a competitive yet cooperative space environment.

In conclusion, astro-economics is a rapidly evolving field that integrates economic models with space science to provide valuable insights into the financial viability and strategic planning required for future space endeavors. Our review underscores the need for continued research and innovation to address the challenges and harness the opportunities presented by the expanding space economy. Policymakers and industry leaders must navigate these complexities thoughtfully to ensure sustainable growth and equitable benefits from space activities. The future of astro-economics holds promise, and with concerted efforts, it can significantly contribute to humanity's quest to explore and utilize outer space.

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