MSc AEROSPACE MANAGEMENT

CIRCULAR ECONOMY FOR SPACE- Master's Thesis

Student Name: Ms. Ashwini MAHAKALKAR

Supervisor: Dr. Victor DOS SANTOS PAULINO

Course: MSc. Aerospace Management (2022-2023)

Date of Submission: 22/08/2023

EXECUTIVE SUMMARY

"CIRCULAR ECONOMY FOR SPACE"

The circular economy can help address the challenges of resource depletion and climate change. Circular economy strategies can help reduce the need for critical materials, improve material efficiency and unlock new sources of critical materials. A circular economy can help reduce the environmental impact of space exploration by making it more sustainable. A circular economy can help reduce debris in orbit and make space exploration more sustainable. The space sector can learn from circular economy practices developed in other sectors and that this can help make space exploration more sustainable. Systems engineering allows systems to be designed and managed to minimize waste and maximize resource efficiency. Institutional capacity building is key to creating the conditions for a successful circular economy.

This thesis explores the role of the circular economy in the triple helix of innovation systems, which is a model that describes the interaction between universities, businesses, and governments in driving innovation. The authors argue that the circular economy can help to create more sustainable and competitive innovation systems. [3]. This thesis provides a comprehensive overview of the circular economy, its history, and its potential benefits. The authors argue that the circular economy can help to address the challenges of resource depletion and climate change. [9]. This thesis examines the potential of circular economy strategies to mitigate critical material supply issues. The authors argue that circular economy strategies can help to reduce the demand for critical materials, improve the efficiency of material use, and develop new sources of critical materials. [27]. This thesis discusses the challenges and opportunities of the circular economy in the context of space exploration. The authors argue that the circular economy can help to reduce the environmental impact of space exploration, while also making it more sustainable. [25]. This thesis explores the potential for a circular economy to be used to manage space debris. The authors argue that a circular economy could help to reduce the amount of debris in orbit and could also make space exploration more sustainable. [77]. This thesis also examines the potential for the space sector to adopt circular economy principles. The authors argue that the space sector can learn from the circular economy practices that have been developed in other sectors, and that doing so could help to make space exploration more sustainable. [83]. It is examined here that the use of circular economy principles in the building industry in Europe. is a major contributor to environmental problems, and that the adoption of circular economy principles could help to reduce the environmental impact of the industry. [72]. This thesis also examines the life cycle environmental impacts of repurposed electric vehicle batteries. The authors developed a method for assessing the environmental impacts of these batteries and find that they can have a lower environmental impact than disposing of them in a landfill. [82]. This thesis examines the role of system engineering in the circular economy. The author argues that system engineering can be used to design and manage systems in a way that minimizes waste and maximizes resource efficiency. [50]. Lastly, this thesis examines the role of institutional capacity-building in the implementation of a circular economy. The authors argue that institutional capacity-building is essential to create the conditions for a circular economy to be successful [63].

Keywords: *circular economy, triple helix of innovation systems, sustainable innovation systems, critical material supply issues, space exploration, space debris, circular economy principles, building industry, electric vehicle batteries, system engineering, institutional capacity-building, sustainability, resource efficiency, waste reduction, pollution prevention, closed-loop production, cradle-to-cradle design, biomimicry, industrial symbiosis, product stewardship, extended producer responsibility*, *eco-design, green procurement*

ACKNOWLEDGEMENT

First, I would like to say that I am grateful to have had the opportunity to study at TBS -Education for one year MSc Aerospace Management course. This journey truly shaped me to become more mature, understanding, and adaptable to face any situation that comes along the way to success. It made me ready to take the next step in my life, going to work and becoming self-sufficient. Before I start contributing to society, writing this master's dissertation is the last step I need to complete. I chose to study MSc Aerospace Management to learn Aerospace Business. I already have learnt Aerospace Engineering and was interested to take a glance at the Business aspects of Aerospace. This gave me a broader view of this Aerospace Industry.

I worked on a strategic project for 5 months under Mrs. Sandra SASSONE (Airbus) on the topic 'Circular Economy for Aviation' and this is when I understood the need for and importance of Circular Economy for space as well. I took this challenge to learn and bring some value to the upcoming generation in the Space Industry. I am happy & contented to have been a small contribution in saving the environment. I hope the readers of this thesis will find motivation to work on Circular Economy in future.

Huge thanks to Mr. Christophe BENAROYA for being available in every step towards my success. My thesis supervisor Dr. Victor DOS SANTOS PAULINO is a very knowledgeable and hardworking person. I thank him for the success of this thesis. I would like to thank TBS Education's administration for being helpful and understanding the need of any administration process required of me.

Table of Contents

Table of Figures

Table of Tables

1. Introduction to Circular Economy

The circular economy for space is a model of production and consumption whose aim is to reduce, reuse or refurbish waste and pollution in the space industry. This can be done by recycling and reusing materials whenever possible.

According to the analysis from United Nations, the world's population is expected to increase by nearly 2 billion persons in the next 30 years, reaching around 9.7 billion in 2015 and it is also possible to reach nearly 10.4 billion in the mid-2080s.

Looking at these numbers which seem to be increasing at a faster pace, the concept of linear economy that is currently used does not seem feasible anymore. The linear economy concept deals with ‘Take Make and Use’. In short, it means that raw materials are taken, processed, and used till the end of their lifecycle.

This is completely where the need for circular economy comes to save the environment. Circular economy implies that reducing waste as minimum as possible. When a product reaches the end of its lifecycle, its materials are kept within the economy wherever possible thanks to recycling. These can be productively used again, thereby creating further value.

One of the major advantages of moving towards a more circular economy could increase competitiveness, stimulate innovation, give a push to economic growth, and create many interesting jobs (700,000 jobs in the EU alone by 2030). Also, the end users or consumers will benefit with more durable and innovative products that will increase the quality of life and save them money in the long term thanks to circular economy.

According to Metabolic’s founder and CEO Eva GLADEK explains the following 7 pillars of the circular economy.

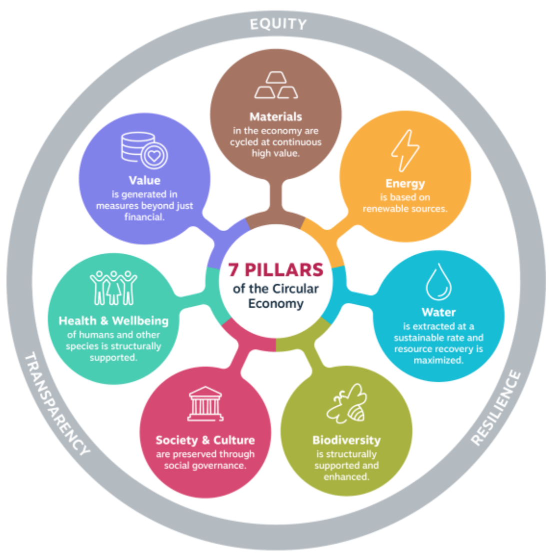

Figure 1 - 7 Pillars of the circular economy

A circular economy for space is a completely new concept, there are different definitions presented and used in this industry.

According to Clara Plata (Technology Transfer from Space to earth in the circular economy field)- “Circular economy is not just a circle of things; it is a matter of circles within a bigger circle.”

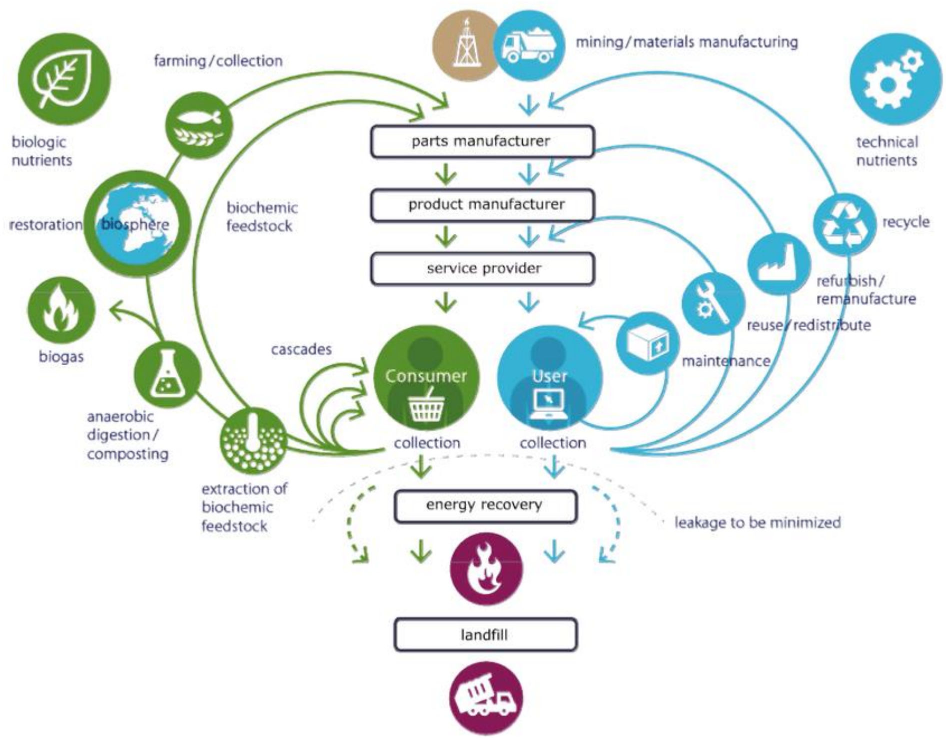

Figure 2 - The Butterfly model - MacArthur Foundation

Harald Friedl (Activist & Accelerator in Circular Economy & Systems Change) says in one of his LinkedIn posts that it is impossible to find one definition. After comparing 221 existing definitions he came up with the following: “The circular economy is a regenerative economic system which necessitates a paradigm shift to replace the ‘end of life’ concept with reducing, alternatively reusing, recycling, and recovering materials”.

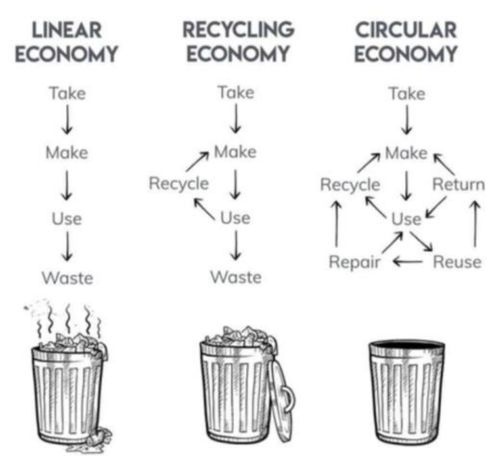

Figure 3 - The paradigm of circular economy

1.1 Present State

It is estimated that there are over 9000 metric tons of space debris in orbit currently. and this number is expected to grow in the coming years as every year there are new satellites and spacecraft being launched into orbit. This growth creates a significant amount of waste including any kind of space debris, which is a major environmental problem.

At present, the use of linear economy is widely accepted around the world. It extracts raw materials, manufacturer's products and then disposes them off as waste. It focuses on selling products, and it completely relies on raw materials. The waste and pollution created by this usage of raw materials can be unsustainable in the long term.

However, circular economy keeps the products and materials in use for as long as possible by extracting the maximum or utmost value from them. It uses the idea of extensive recycling and reusing of materials thereby reducing huge amount of waste and pollution that in turn will be more sustainable in the long term.

1.2 What Got Us Here?

It's a known fact that there is an increasing demand for space-based services such as satellite communications, earth observation, lunar missions, military missions, space tourism etc. The cost involved in launching satellites into orbit is huge. Launching a single satellite into space can cost anywhere between $10 million and $400 million depending on the vehicle used. Even after managing this cost the need for new technologies to make space exploration more sustainable is still a question.

Every time a business model is created, there is perception for a need to think "circular" rather than "linear". It elucidates as we prioritize circularity over linearity of the business models, there are ample chances to reduce this waste and pollution leading to a more sustainable space exploration.

Therefore, based on the questions of sustainability and economy it would be a better idea to think about circular economy and progressively cascade the idea of linear economy.

Due to a questionable fact that why industries would consider circular economy since there is a lack of infrastructure for recycling and reusing the materials. There is a dire need for international co-operation to come up with a uniform or unique solution or law that will help achieve a sustainable space exploration opportunity in future.

2. Aim & Research Question

"How Circular Economy for Space could be beneficial for environment and for the emerging space businesses?".

Space business is emerging, and it will be great to learn about how space business can be made more economical and sustainable. The idea is not to focus only on profits in terms of cash flow, but also profits in terms of helping the environment and exploring space.

Here are some concrete ways that the circular economy can benefit the space sector and the environment:

Waste reduction: The circular economy can help reduce waste in the space sector by reusing and refurbishing spacecraft and their components, recycling spacecraft materials and other space debris, and making spacecraft and their components more modular and easier to disassemble and reassemble.

Pollution Reduction: The circular economy can help reduce pollution in the space sector by using bio-based materials that can be composted or biodegraded after use and by developing new technologies to extract and use space resources.

Ecosystems Protected: The circular economy can help protect ecosystems in space by reducing the amount of space debris that can damage satellites and other spacecraft, and by developing new technologies to sustainably mine and use space resources.

Cost Reduction: The circular economy can help reduce costs for emerging space companies by reducing the need to purchase new materials and components and increasing resource efficiency.

More innovation: The circular economy can help drive innovation in the space sector by creating new opportunities for companies to develop and apply new technologies and services.

Reputation Enhancement: The circular economy can help improve the reputation of emerging space companies by demonstrating their commitment to sustainability and environmental protection.

3. Methodology

3.1 Research Approach:

This thesis is a mix of both qualitative and quantitative research. The reason for taking the mix of both the research approaches was to understand the need in all the way possible. It helped understand the comprehensive nature of the thesis, the triangulation approach which involves comparing the findings from different research methods to enhance the credibility and validity of the research to address my research question. It helped me to go in depth and explore the statistical analysis.

The qualitative methods provided insights into "why" and "how" questions whereas the quantitative methods helped to address "what" and "how many" questions. It also incorporated the larger data into a simplified version where the research got very generalized conclusions. The mix of this research captures the richness of motivation results and provides a more detailed view of the research question. This indeed helped to bring a larger context into the thesis. Mixing both the qualitative and quantitative approach helped both technical and non-technical stakeholders to understand the quality of this research in a better way.

3.2 Data Collection Methods:

For the data collection two interviews were conducted to address the basic structure of this research. Both the professionals who were interviewed are working very hard towards circular economy and making sure that the future generation understands the real need of circular economy for space. Firstly, Mr. Frank KOCH is a well-known entrepreneur who is working towards clearing space debris and he has been selected by the Paris peace forum for his involvement in the circular economy.

Secondly, Mrs. Sandra SASSONNE, is an environment officer at Airbus commercial and when an opportunity was presented to work under her for one of the strategic projects on circular economy in aviation, she inspired me to take this topic forward and learn about circular economy for space. Hence, these two interviews' aides to learn about the real need of circular economy, what is the present state scenario and what could be the future that we would get to see if such implementation of circular economy for space.

3.3 Interview Protocol:

The interview was divided into smaller parts. The first was to know the background of the professionals, their experiences, what they are working on, and the description of their job position in their respective organizations.

Furthermore, it answered the questions of environmental benefits of adopting circular economy approach in the space industry, some innovative approaches or concepts that might revolutionize the circular economy in space and how potentially the but in samples of space debris mitigation and removal efforts be used for circular economy in space.

Lastly, this section involves the future aspects of circular economy and how they envision the space industry and the space business after the implementation of circular economy for space.

The interview was concluded by getting to know what could be questioned more to learn the real need of circular economy for space.

3.4 Data Collection Procedures:

The interviews were conducted online via Google meet platform. Both the interviews were recorded and kept as proof for future reference.

3.5 Ethical Considerations:

This thesis has a very generalist point of view hence the references, understandings and ideas are not bound by any confidentiality. The idea of the interview was not to understand any specific company or compare the companies but to get an overview of the industry and understand the real need of implementing Circular Economy for Space.

3.6 Triangulation:

While undertaking the research, a correlation was required to validate whether the interviews and the findings match, the data and representation that was found while referencing some published papers, are in-line to what the professionals have answered.

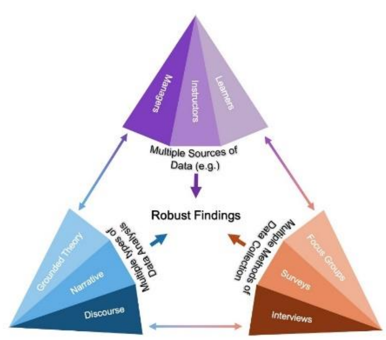

Figure 4 - Triangulation Method for findings

Method	Description
Data triangulation	Using multiple data sources, such as interviews and observations.
Methodological triangulation	Using multiple research methods, such as quantitative and qualitative methods.
Theory triangulation	Using multiple theories to interpret the data.
Person triangulation	Getting feedback from multiple people, such as participants, experts, and peers.
Time triangulation	Collecting data at different points in time.

Table 1 - Triangulation Method for findings

3.7 Limitations:

Since there are variety of nomenclature involved in circular economy like reusing, refurbishing, or recycling of the materials which are used to build the spacecraft, space debris, or extend their life in the orbit, or using these materials in any other industry like construction, furniture, aviation, this research limits to more generalist approach of handling and transforming towards circular economy.

3.8 Data Presentation:

The data presented in the results and discussion section of this thesis support the findings in a logical sequence that follows the research question. Followed by presenting these raw data and key findings with interpretation. The raw data was tables, graphs, charts, and figures that were used to visually represent quantitative data.

Most importantly, the connections and conclusions derived were linked with my findings back to the research question or the objective that was introduced at the beginning of the thesis. The following were highlighted: similarities, differences, and areas of convergence or divergence. Abstract explanations for the patterns and trends were interpreted which reflect on the growth of circular economy within the given period.

The broader implications of the research context were also addressed. For example, how would the business for the space industry get benefited after the implementation of this concept of circular economy.

4. Growing Demand of Circular Economy

The space industry is growing rapidly and the number of satellites in orbit is expected to double by 2030. This growth puts pressure on the environment, as satellites and other space debris can pose a hazard to other spacecraft and even the International Space Station. The circular economy is a production and consumption model that aims to keep resources usable for as long as possible.

It can be applied to the space industry in several ways, such as:

Developing satellites that are more durable and less prone to failure: This can help reduce the amount of space debris generated.

Develop technologies to remove existing space debris from orbit: This can help clean up the space environment and reduce the risk of collisions.

Reuse and recycle materials from old satellites and other spacecraft: This can help conserve resources and reduce the need to launch new materials from Earth.

Manufacturing Materials in Space: This could be done using resources such as sunlight, which is abundant in space. This would reduce the need to launch materials from Earth, which is a major source of pollution.

The circular economy is a promising way to make the space industry more sustainable. By adopting these practices, the space industry can help protect the environment and ensure the long-term sustainability of space exploration.

Here are some concrete examples of how the circular economy is applied to the space industry:
The European Space Agency (ESA) developed a project called Clean Space to remove space debris from orbit. The project will use a variety of technologies, including a robotic arm that can capture debris and remove it from orbit.

Astroscale is developing a spacecraft called End-of-Life Services (ELS) that can service and de-orbit retired satellites. The ELS spacecraft will use a robotic arm to acquire the satellites and then resupply them or de-orbit them.

The company SpaceIL develops a technology called Luna-Globe, with which water can be extracted from lunar regolith. This water could be used to produce fuel and other resources for future missions to the moon.

These are just a few examples of how the circular economy is being applied to the space industry. As the space industry continues to grow, the demand for circular economy solutions will only increase. The circular economy benefits both the space industry and the environment.

4.1 What is the Future of Space Exploration?

The future of space exploration is a topic that has been discussed extensively for many years. There are many different ideas about what the future holds, but some of the most common possibilities include:

Manned missions to Mars: This are perhaps the most popular vision for the future of space exploration. Many countries are currently developing plans for manned missions to Mars, and some believe this could happen in the next few decades.

Commercial Space Tourism: This is another rapidly growing area of space exploration. Companies like SpaceX and Virgin Galactic are developing suborbital and orbital tourist flights, and some believe commercial space tourism could become a reality in the next few years.

Deep Space Exploration: This refers to missions into the outer solar system and beyond.
This is a more challenging and expensive endeavour, but there is growing interest in exploring places like Jupiter's moons, Saturn's rings, and the outer planets.

Space Mining: Refers to the extraction of resources from space, such as water, metals, and minerals. Space mining could provide us with new resources and help make our planet more sustainable.

Space Habitats: Refers to the development of permanent human settlements in space. Space habitats could give us a place to live and work outside of Earth and help us explore the solar system more easily. These are just some of the possibilities for the future of space exploration. The exact path we take will depend on several factors, including technological advances, financial resources, and political will.

However, one thing is certain: the future of space exploration is bright.

In addition to the above, here are some other trends that are likely to shape the future of space exploration:

The Rise of Private Space Companies: Private companies play an increasingly important role in space exploration. Companies like SpaceX and Blue Origin are developing new technologies and launching their own missions. This should result in a more diverse and innovative space industry.

This is important to share resources and expertise and ensure space exploration is conducted safely and sustainably.

Focus on sustainability: Space exploration is becoming more sustainable. New technologies are being developed to reduce the environmental impact of space missions. This is important to ensure that space exploration can continue for generations. The future of space exploration is full of possibilities.

The figure below depicts the emergence of new space services that have much more potential and accuracy than the traditional space.

These services include thoughts of debris mitigation and removal which is currently creating a havoc in the lower earth orbit, satellite services such as Internet for all and earth observation, space tourism for providing travel two space for tourists, in-space manufacturing that includes production of goods and materials in space and space mining which deals with extraction of resources from asteroids and other bodies in space.

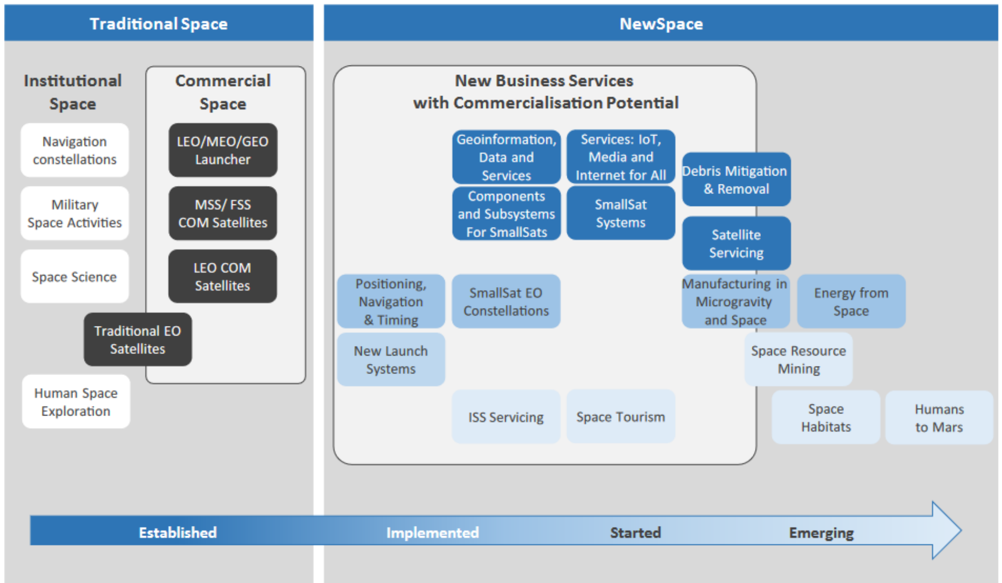

Figure 5 - Existing and new business services

Furthermore, it can also be seen that launch industry and satellite manufacturing are the most mature stages of the space industry. Looking at this demand for growth in the space industry, the need for materials will be unimaginable in future. The space business will grow and if we don't look at the environmental side of the usage of materials, we will not be able to explore these new advancements in future.

Of course, these wide areas that are emerging in the space industry give a new way for businesses to take birth. These businesses are unique and not equal to the businesses that are done commonly. It's called unique because the risk in space businesses is much higher than other commercial industries. Sustainability is the biggest issue that must be tackled while we grow in the space business. Hence for the evolution, we need to have a circular business model and progress only in that way in this space industry.

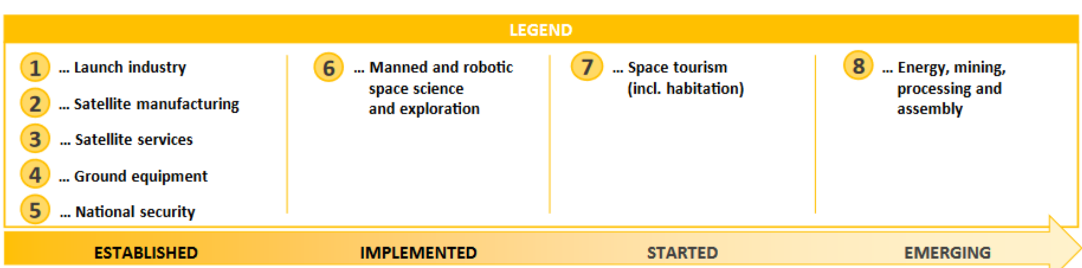

Figure 6 - Space sector value chain & market segments

4.2 Current cost effectiveness scenario

Talking about the reduction in costs for the next generation of launchers, the figure below gives the difference in cost percent from prior generation to the next generation launchers.

Technically speaking, the decrease in weight has made rockets more efficient and a bit less expensive to launch. This decrease in weight is possible because of the new materials, such as carbon composites, that are stronger and lighter done old traditional materials.

Prior generation		Next generation		Change
Rocket	$/kg to LEO	Rocket	$/kg to LEO	%
Proton	4.565	Angara A5	4.167	–9 %
Ariane 5	8.476	Ariane 6	4.762	–44 %
Falcon 9*	4.654	Falcon 9 FT*	2.719	–42 %
N/A	N/A	Falcon Heavy*	1.654	N/A
H-IIA/B	6.818	H3	5.000	–27 %
GSLV	9.400	LVM3	7.500	–20 %
Saturn V	22.857	SLS	3.268	–86 %
Atlas V/Delta IV	11.093	Vulcan	6.378	–43 %

Figure 7 - Dropping specific launch costs for next generation of launchers

Looking at this boom in the space industry, a very new concept of space achievements has come outright. This is called "Space Age 2.0" where the demand for different missions with their investments are mentioned. This timeline is a very useful way to understand the history and future of space exploration. It has made drastic progress. This timeline also urges us to see the demand in the space industry.

Figure 8 - Space age 2.0 in a nutshell

4.3 Current Business Models

It is essential to understand the primary B2B business models and the primary B2C business models to better understand the launch industry. The B2B stands for business to business, and it clearly refers to businesses that provide satellite services to other businesses. The B2C stands for business to consumer, and it refers to businesses that provide satellite services directly to consumers.

4.3.1 B2B Model:

A business-to-business (B2B) model is a business transaction in which goods or services are exchanged between two companies. In the space industry, B2B models are used to offer a range of products and services such as:

<u>Satellite Imagery:</u> Companies that collect satellite imagery sell their products to other companies such as governments, insurance companies, and farmers.

<u>Launch Services:</u> Companies that launch rockets sell their services to other companies, such as satellite operators and space tourism companies.

<u>Spacecraft Components</u>: Companies that manufacture spacecraft components sell their products to other companies, such as satellite manufacturers and launch vehicle suppliers.

<u>Engineering Services</u>: Companies that provide engineering services such as design and analysis sell their services to other companies such as satellite operators and launch vehicle providers.

<u>Training Services:</u> Companies that provide training services such as astronaut training sell their services to other companies such as space agencies and commercial space companies.

B2B models are becoming more common in the space industry as the industry becomes more commercial and diversified. Because companies are looking for more efficient ways to procure the goods and services they need. B2B models can help companies save money, increase efficiency, and reduce risk.

These are some of the benefits of using a B2B model in the space industry:

<u>Efficiency:</u> B2B models can help companies save time and money by eliminating the use of a middleman.

<u>Better Relationships:</u> B2B relationships can be more beneficial than B2C relationships because companies are more likely to have similar goals and objectives.

<u>Reduced Risk:</u> B2B models can help companies reduce their risk by working with trusted partners.

4.3.2 B2C Model:

The business-to-consumer (B2C) model is a commercial transaction in which a company sells goods or services directly to an individual consumer. In the space industry, B2C models are used to offer consumers a variety of products and services, such as:

Space tourism: Space tourism companies sell their services directly to consumers.

Educational Products: Companies that develop space-related educational products sell their products directly to consumers.

Space-Themed Merchandise: Businesses that sell space-themed merchandise, such as toys, clothing, and accessories, sell directly to consumers.

Space Services: Companies that provide space services, such as satellite internet access, sell their services directly to consumers.

B2C models are becoming more common in the space industry as the industry becomes increasingly commercialized and open to the public. Consumers are increasingly interested in space and willing to pay for space-related products and services.

Here are some of the advantages of using the B2C model in the space industry:

Direct contact with customers: B2C models allows companies to contact customers directly. This can help businesses better understand their customers' needs and preferences.

One-to-One Marketing: B2C models allow companies to target marketing messages to specific consumers. It can help businesses increase sales and improve customer satisfaction.

Brand Awareness: B2C models can help companies increase their brand awareness and create a positive image in the minds of consumers.

It can help you build relationships with your customers, understand their needs, and improve your bottom line.

Here are some examples of B2C companies in the space sector:

SpaceX: SpaceX sells tickets to space tourists and provides commercial satellite launch services.

Virgin Galactic: Virgin Galactic offers scenic suborbital spaceflights.

Planet Labs: Planet Labs sells satellite imagery to corporations and governments.

SpaceIL: SpaceIL is developing a lunar lander that collects samples from the moon and sends them back to Earth.

The Space Foundation: The Space Foundation makes Space educational products and services available to the public.

The diagram below shows these 2 business models and the connection between them. It can help businesses to understand the different options available to them and to be informed while making decisions about their business models.

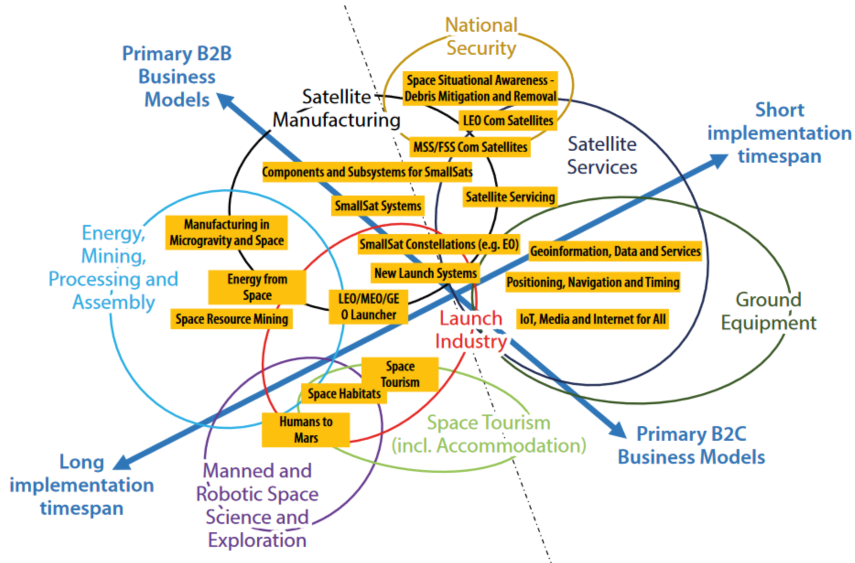

Figure 9 - A landscape of space business services, business models and segment

4.4 Focussing on European Space Market

The European space market is a fast-growing market with a revenue of €8.257 billion in 2022. The market is expected to grow at a CAGR of 3.5% from 2022 to 2028, reaching €10.022 billion in 2028.

The growth of the European space market is being driven by several factors including:

The growing demand for satellite imagery and data: Satellite imagery and data are used for a variety of applications, such as earth observation, navigation, and communications. The development of new technologies: new technologies such as small satellites and constellations are making space more accessible and affordable.

Increasing collaboration between the public and private sectors: Governments and private companies are working together to develop and launch new space projects.

The European space market is divided into the following segments:

Satellites: This segment includes the sale of satellites, satellite components and satellite services.

Launchers: This segment includes the sale of launchers and launcher services.

Ground Stations: This segment includes the sale of ground stations and ground station services.

Space Applications: This segment includes the sale of space applications such as satellite imagery and data, navigation, and communications.

The European space market is a dynamic and growing market. Here are some of the key trends shaping the European space market:

The Growing Demand for Satellite Imagery and Data: Satellite imagery and data are used for a variety of applications, such as earth observation, navigation, and communications.

Demand for satellite imagery and data is expected to continue to grow in the coming years as more companies and governments adopt these technologies. This collaboration helps reduce the cost of space exploration and enables more ambitious projects to be carried out. The European space market is a promising market with a lot of potential. The market is expected to continue growing in the coming years due to the above factors.

For example, the following figure shows the "*Thales Alenia Space*", a European space company, shows a positive trend that leads the way in telecom satellite market as space becomes a strategic priority. This explains the full potential and scope of the space market players in the European union.

Figure 10 - Thales Alenia Space – 2022 a full-speed year

4.5 Space market - before & after SpaceX

SpaceX revolutionized the space market by developing a new approach to rockets. The company's Falcon 9 rocket is reusable, which significantly reduces launch costs. SpaceX has also used new technologies like 3D printing to make its rockets more affordable and efficient. SpaceX innovations have reduced the cost of getting a satellite into orbit by up to 50%.

This has made the space more accessible to a wider range of businesses and organizations. It has also led to a boom in the space industry as new companies entered the market and developed new applications for space technology. In terms of innovation, SpaceX has also made significant strides in developing new technologies for space exploration. The company's Dragon spacecraft is the first commercial spacecraft to dock with the International Space Station. SpaceX is also developing a new rocket called Starship that will take humans to Mars.

The SpaceX innovations had a huge impact on the space market.

Here are some specific examples of how SpaceX has reduced costs and innovated in the space market:

Reusable Rockets: SpaceX's Falcon 9 rocket is reusable, which significantly reduces launch costs.

The company has reused its rockets multiple times and plans to make them reusable even more in the future.

3D Printing: SpaceX uses 3D printing to make parts for its rockets. This technology allows the company to produce parts faster and at lower cost than traditional methods.

Small Satellites: SpaceX is also developing small satellites, also known as "CubeSats. These satellites are much smaller and less expensive than traditional satellites. This makes them more affordable for companies and organizations looking to leverage space technology.

Starship: SpaceX is developing a new rocket called Starship that will take humans to Mars. Starship is still in development but has the potential to revolutionize space travel. The SpaceX innovations are having a huge impact on the space market. The company makes space more accessible and affordable and helps drive innovation in the space industry.

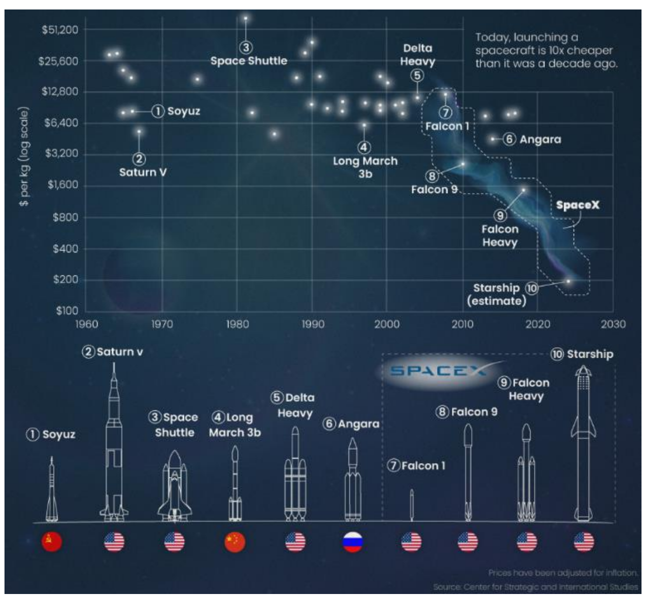

Figure 11 - The Cost of Space Flight Before and After SpaceX

4.6 Satellites Demand

With the increasing use of space technology by companies and organizations, the demand for satellites is growing exponentially. The current number of satellites in orbit is about 2,500, but this number is expected to increase significantly in the coming years. The projected number of LEO satellites over the next 10 years is staggering, with some estimates exceeding 100,000. This growth is due to several factors, including growing demand for satellite imagery and data, the development of new technologies, and growing collaboration between the public and private sectors.

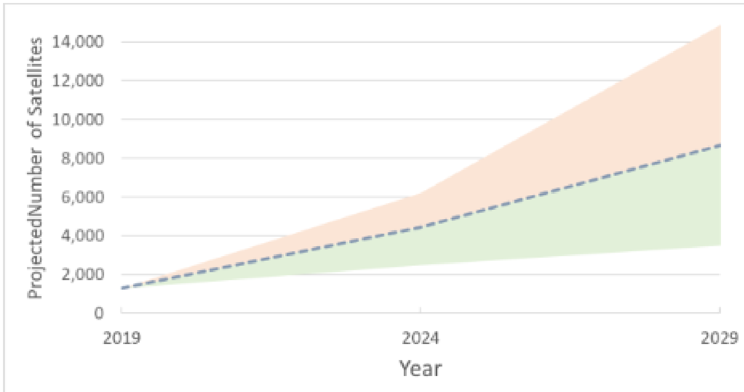

Figure 12 - The projected number of LEO satellites in the next 10 years

The development of the satellite industry opens new opportunities for companies and organizations. Companies that can develop and deploy satellite technology are well positioned to benefit from this growth.

<u>Navigation</u>: Satellites are used to provide navigation services such as GPS. Many businesses and organizations use these services, including cruise lines, shipping companies and the military.

<u>Communications:</u> Satellites are used to provide communication services such as voice and data transmission.

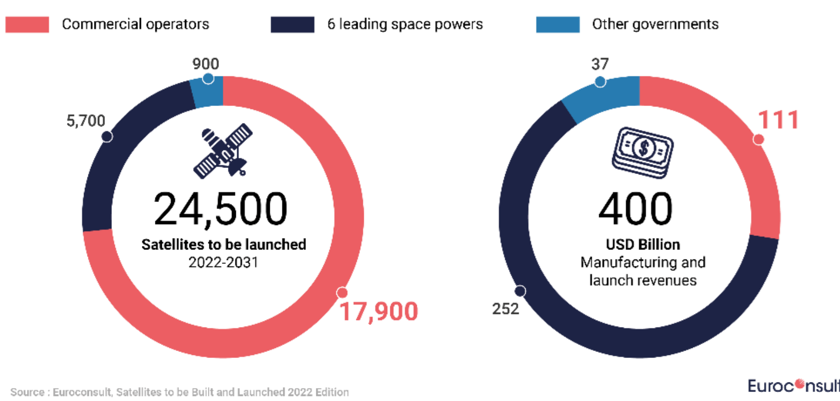

Figure 13 - Satellite quadruple demand over the next decade

These services are used by businesses, governments, and individuals around the world.

Telecommuting: Satellites are used to provide telecommuting services, allowing people to work from anywhere in the world. This growth is fuelled by the development of new technologies such as small satellites and constellations, and by increasing collaboration between the public and private sectors.

The satellite industry is a fast growing and evolving industry and companies that can adapt to this growth will be well placed to succeed.

Here are some of the new technologies driving the development of the satellite industry:

Small satellites: small satellites, also known as CubeSats, are becoming increasingly popular. Their satellites are cheaper to launch and operate than traditional satellites.

Constellations: Constellations are groups of satellites assembled in orbit. This allows them to continuously cover a specific area.

Artificial Intelligence: Artificial intelligence is used to improve the performance of satellites. For example, AI can be used to identify and track objects in space. The development of the satellite industry is also fuelled by growing collaboration between the public and private sectors. Governments and private companies work together to develop and launch new space projects. This collaboration reduces the cost of space exploration and allows for more ambitious projects.

5. Microbes for Space

Microbes are ubiquitous in the universe, including in space. They have been found on the surface of asteroids, comets and even in the Martian atmosphere. Scientists are interested in studying microbes in space because they can help us understand the origins of life and the possibility of life existing on other planets. Microbes can survive in extreme environments, including the vacuum of space. They also withstand high radiation and temperature loads. This makes them very well suited to life in space, where conditions are often harsh.

Scientists are studying microbes in space for several reasons. One reason is to understand how they survive in extreme environments. This knowledge could help us develop new ways to protect astronauts from the harsh conditions in space. Another reason to study microbes in space is to learn more about the origin of life. Scientists believe life on Earth may have originated from microbes that came from outer space. By studying microbes in space, we can learn more about the conditions necessary for life to exist. Finally, scientists study microbes in space to explore the potential for life on other planets. If we could find microbes on Mars or other planets, it would be strong evidence that life could exist outside of Earth.

The study of microbes in space presents several challenges. One challenge is that it is difficult to collect and transport microbes from space. Another challenge is that studying microbes in the harsh conditions of space is difficult. Despite the challenges, scientists are making strides studying microbes in space. They have developed new methods of collecting and transporting microbes and have developed new methods of studying microbes in the harsh conditions of space. The study of microbes in space is a rapidly growing area of research.

Scientists are constantly making new discoveries and learning more about the potential for life beyond Earth.

Here are some specific microbes found in space:

Bacillus subtilis: This Bacillus subtilis bacterium is found in soil and water on Earth. It was the first bacterium found in space in 1994.

Figure 14 - Bacillus subtilis

Staphylococcus aureus: This bacterium is a common cause of human infections. It was found on the surface of the International Space Station in 2008.

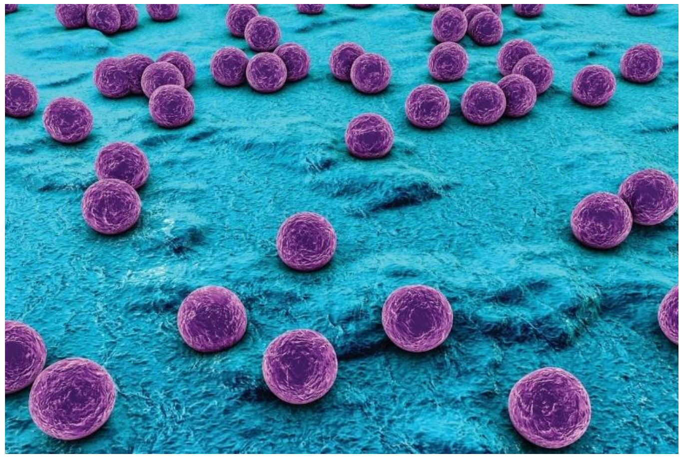

Figure 15 - Staphylococcus aureus

Micrococcus luteus: This bacterium is also found in soil and water on Earth. It was found on the surface of a comet in 2014.

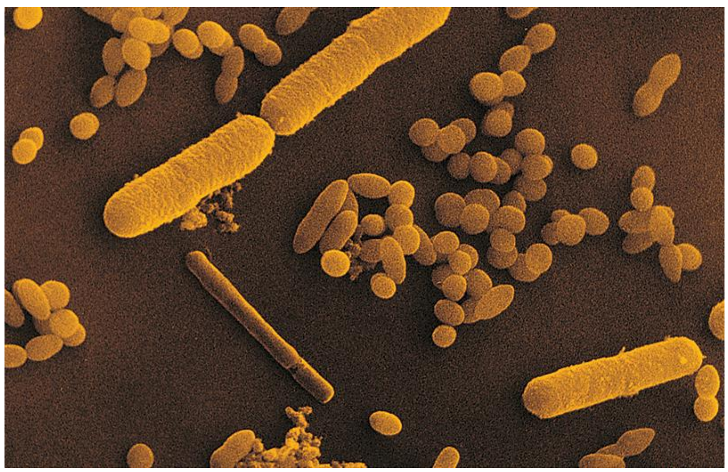

Figure 16 - Micrococcus luteus

Deinococcus radiodurans: This bacterium is known for its ability to withstand high levels of radiation. It was found in the Martian atmosphere in 2015.

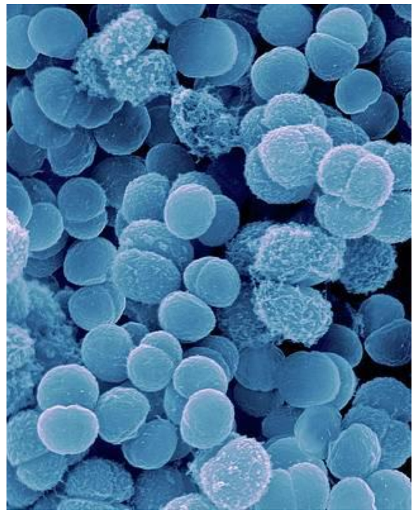

Figure 17 - Deinococcus radiodurans

These are just a few of the many microbes that have been found in space. Scientists continue to search for new microbes in space and learn more about the potential for life beyond Earth.

6. Life Extension of Astronauts

The idea of extending the lifespan of astronauts is intriguing. It would allow us to send humans on longer missions to explore other planets or even colonize space. Before that can happen, however, several challenges remain to be overcome. One of the greatest challenges is the effects of radiation on the human body. Astronauts are exposed to high levels of radiation during space travel, which can damage cells and DNA. This can lead to cancer and other health problems.

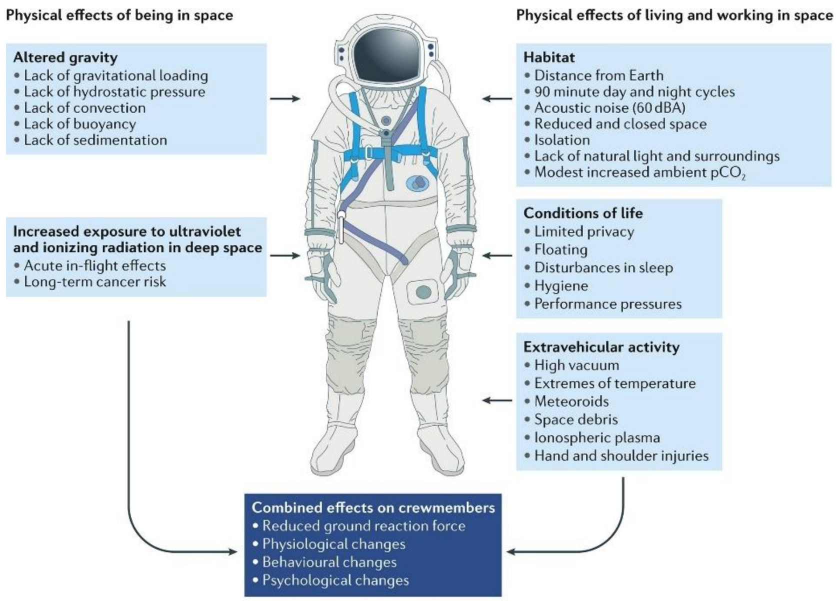

Figure 18 – Physical effects of being in Space - Life Extension of Astronauts

Another challenge is the lack of gravity in space. This can lead to muscle and bone loss and other health problems. scientists are working on different ways to address these challenges.

One approach is to develop new methods to protect astronauts from radiation.

Another approach is to develop drugs or therapies that can help repair the damage caused by radiation.

Scientists are also working on ways to create artificial gravity in space. This could be done using a rotating spacecraft or using magnetic fields. Developing technologies to extend astronaut life is a complex and challenging task.

However, the potential rewards are great. If we can overcome the challenges, it could open the possibility of human exploration of the solar system and beyond.

Here are some specific technologies being studied to extend astronaut life:

Radiation protection: Scientists are developing new materials and methods to protect astronauts from radiation. A promising approach is the use of water as a radiation shield. Water is a good radiation absorber; it is also relatively light and easy to transport.

Drugs and Therapies: Scientists are developing drugs and therapies that can help repair the damage caused by radiation. One promising drug is amifostine, which has been shown to protect against the effects of radiation in animal studies.

Artificial Gravity: Scientists are researching ways to create artificial gravity in space.

The spinning spacecraft would create artificial gravity by spinning around an axis. This would create a centrifugal force that would mimic the effect of gravity. Magnetic fields could also be used to create artificial gravity. Magnetic fields can be used to trap charged particles, and these particles could be used to generate a force that mimics the effects of gravity.

Figure 19 - Artificial Gravity – Spinning Spacecraft

These are just some of the technologies being studied to extend astronaut life. The development of these technologies is still in its infancy, but they have the potential to revolutionize space travel.

7. Making Oxygen, Water and Nutrition from Waste

In space, every resource is precious. Astronauts must be able to recycle their waste to survive long-term missions. Many technologies are being developed to extract oxygen, water, and food from space debris. One way to create oxygen from waste is through a process called regenerative life support. This system uses microorganisms to break down organic waste, such as urine and leftover food, into carbon dioxide and water. Carbon dioxide can be used to produce oxygen in a process called electrolysis.

Purified water can be reused for drinking, bathing, and other purposes. Food can also be recycled from waste in space. One possibility is the production of microbial proteins. This process uses microorganisms to convert organic waste into protein. The protein can then be used to feed the astronauts. These technologies will help provide astronauts with the resources they need to survive and thrive in space.

Here are some specific technologies being researched to create oxygen, water, and food from space debris:

Regenerative Life Support: This is a process that uses electricity to split water molecules into oxygen and hydrogen. Oxygen can be used for respiration and hydrogen for fuel.

Water disinfection: This is a process that uses filters to remove contaminants from urine and other wastewater.

Microbial Protein Production: This is the process by which microorganisms convert organic waste into protein. This protein can then be used to feed astronauts.

These are just some of the technologies being studied for extracting oxygen, water, and food from space debris. Although these technologies are still in their infancy, they have the potential to revolutionize space travel.

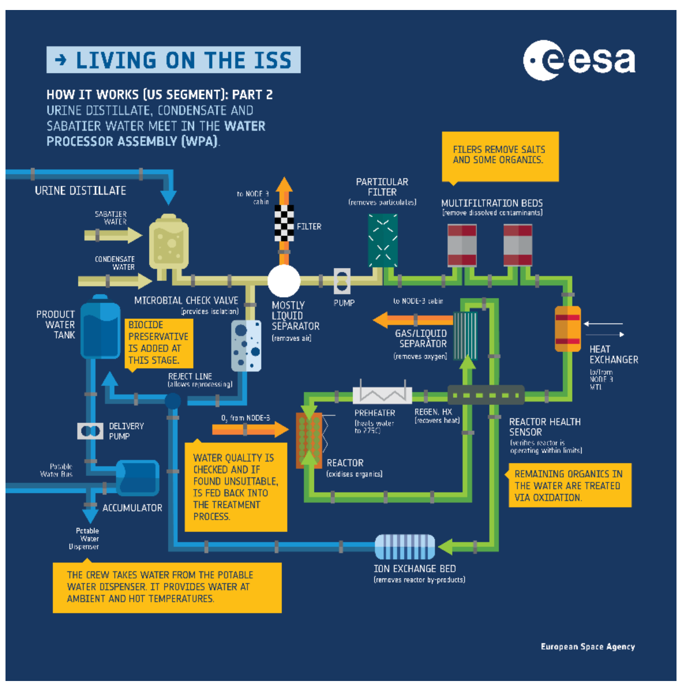

Figure 20 - Water reclamation system for space

8. Making Oxygen from released Carbon-di-oxide of Astronauts

One of the greatest challenges in space travel is the limited availability of resources. Astronauts must carry everything they need, including oxygen, water, and food. This can be very expensive and difficult, especially for long-term deployments. One way to reduce the number of resources astronauts must carry is to create oxygen from the carbon dioxide they exhale. Carbon dioxide is a byproduct of respiration and is produced by all living things.

There are several ways to produce oxygen from carbon dioxide. One way is to use a process called regenerative life support. This system uses microorganisms to break down organic waste, such as urine and leftover food, into carbon dioxide and water. Carbon dioxide can be used to produce oxygen in a process called electrolysis. Oxygen can be used for breathing and hydrogen for fuel. Another way to create oxygen from carbon dioxide is through a process called solid oxide electrolysis.

The water molecules are separated into oxygen and hydrogen using a solid oxide membrane. Regenerative life support and solid oxide electrolysis are promising technologies for producing oxygen from carbon dioxide in space.

Here are some quantitative statistics on how much oxygen can be made from carbon dioxide:

According to a study by the National Aeronautics and Space Administration (NASA), about 800 litres of oxygen can be made from one kilogram of carbon dioxide. That means a single astronaut equipped with the 's regenerative life support system could produce enough oxygen to breathe for about 20 days.

A solid oxide electrolysis system could produce even more oxygen, about 1,000 litres per kilogram of carbon dioxide. The development of technologies to produce oxygen from carbon dioxide is crucial for long-term space missions. These technologies will help reduce the cost and complexity of spaceflight and allow astronauts to spend more time in space.

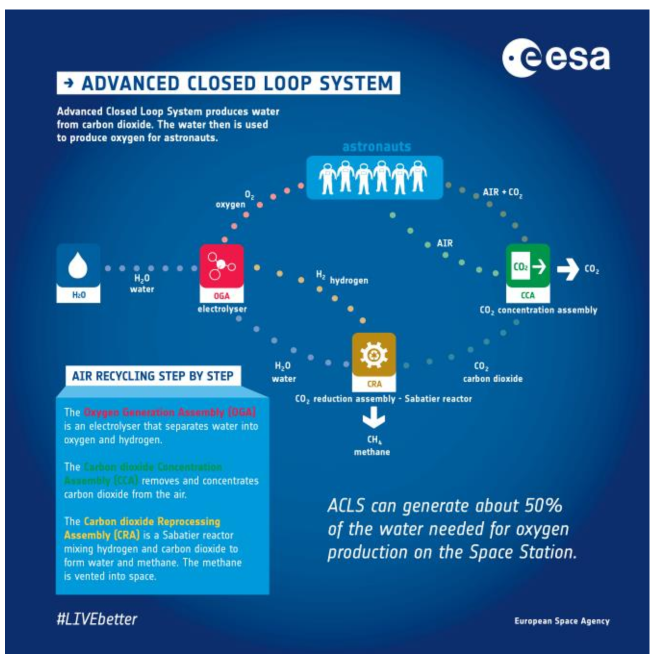

Figure 21 - Advanced closed-loop system for oxygen recycling

9. In-Orbit Repair

In-orbit repair involves repairing a spacecraft or other object in space without bringing it back to Earth. This can be done for a variety of reasons, such as fixing a malfunction, upgrading the spaceship, or increasing its lifespan. There are many different techniques that can be used for in-orbit repairs. A common technique is to manipulate the spacecraft with a robotic arm. This can be used to replace damaged components, install new devices, or carry out other repairs.

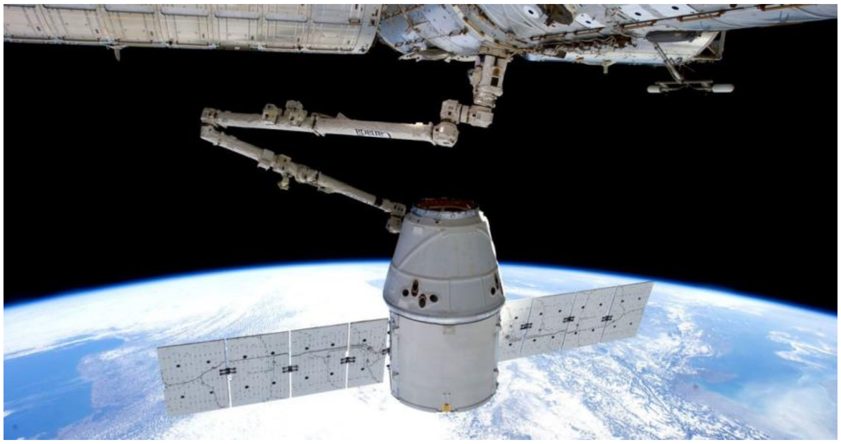

Figure 22 - In-orbit repair - Spacecraft

Another repair technique in orbit is the use of astronauts. Astronauts can be sent to the spacecraft to manually perform repairs there. This is a more complex and expensive technique but may be necessary for repairs that are too difficult or dangerous for a robotic arm. Here are some quantitative statistics on in-orbit repairs: The first in-orbit repair of was made in 1965 when Gemini-4 astronauts repaired a damaged heat shield.

Figure 23 - In-orbit repair - Astronauts

Since then, astronauts and robotic arms have performed more than 200 in-orbit repairs. The most complex in-orbit repair was performed in 2008 when astronauts on the Space Shuttle Atlantis repaired the Hubble Space Telescope. On-orbit repair is a complex and challenging task, but essential to spacecraft maintenance and operations.

As space exploration becomes more ambitious, the need for in-orbit repairs is likely to increase.

Here are some of the on-orbit repair challenges: The environment in space is very harsh, with extremes of temperature, radiation, and vacuum. This can make it difficult to use robotic arms and other devices. The distance between Earth and the spacecraft can be long, making communication and controlling the repair process difficult. Repair costs in orbit can be high, especially for complex repairs.

Despite its challenges, in-orbit repair is a key capability for space exploration. It enables spacecraft to be repaired and maintained, extending their lifespan, and ensuring they can continue to operate safely and efficiently.

10. Active Debris Removal

Active Debris Removal (ADR) is the removal of space debris from orbit. This can be done using different techniques, such as:

<u>Track and Capture:</u> Involves using a spaceship to track and capture a piece of debris. The debris can then be returned to Earth or desorbed.

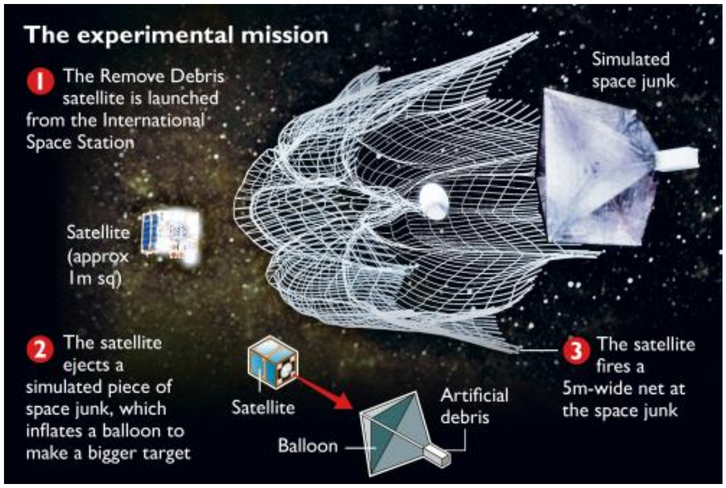

Figure 24 - Track and Capture - ADR

<u>Kinetic Impactor:</u> Involves using a spacecraft to impact debris at high speed. The impact breaks the debris into smaller pieces, which then fall out of orbit naturally.

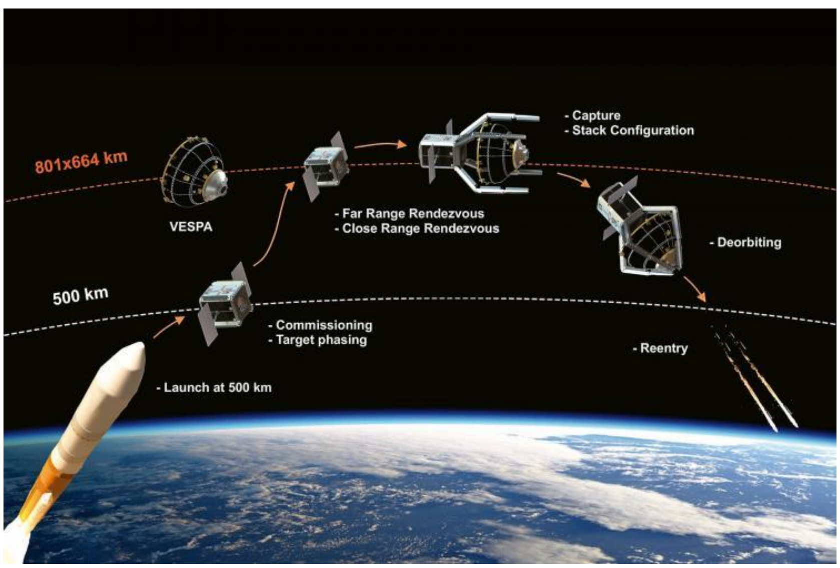

Figure 25 - Kinetic Impactor - ADR

<u>Laser Ablation</u>: In laser ablation, a piece of debris is heated until it vaporizes. The evaporated residues are then naturally desorbed.

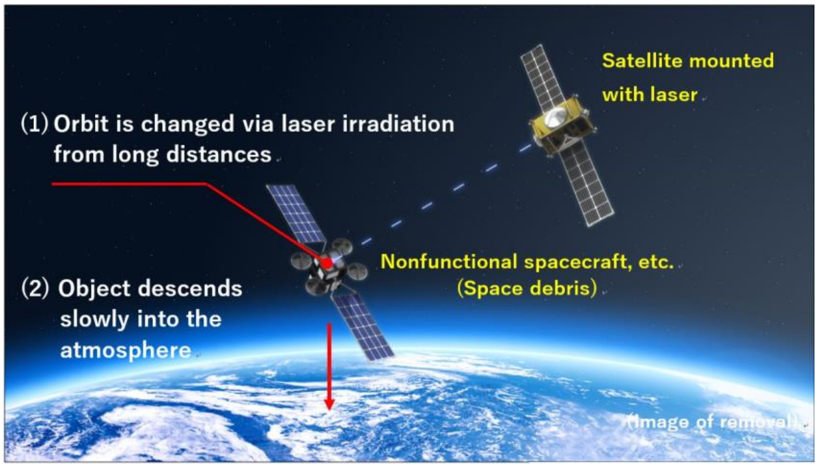

Figure 26 - Laser Ablation - ADR

The anticipated market for Active Debris Removal (ADR) services is growing rapidly. According to a report by Grand View Research, the market is expected to reach $1.2 billion by 2028.This growth is being driven by the growing number of satellites in orbit, as well as growing awareness of the dangers of space debris.

The number of satellites in orbit is forecast to increase from around 2,600 in 2022 to over 10,000 in 2030.This increase in the number of satellites will lead to an increase in space debris.

Increasing awareness of the dangers of space debris: The dangers of space debris are becoming increasingly well known. Debris can collide with satellites, causing damage or even destruction. It can also pose a threat to astronauts and spacecraft.

The ADR market is still at an early stage of development but is growing rapidly. As the number of satellites in orbit continues to increase, demand for ADR services is expected to increase.

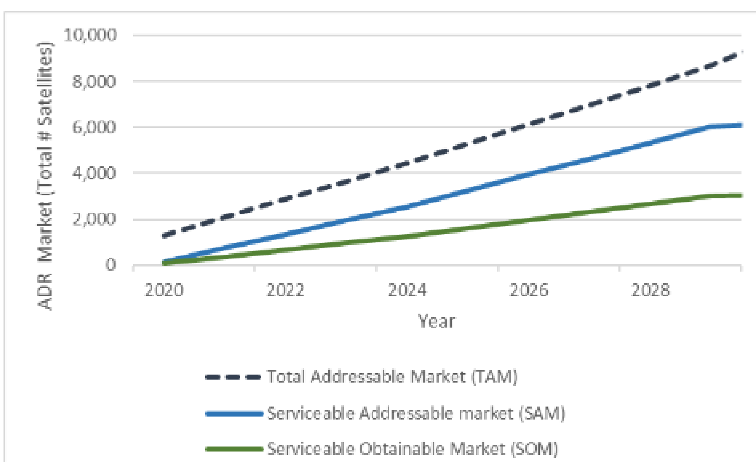

Figure 27 - The projected market for ADR services

Here are some of the challenges facing the ADR market:

<u>High ADR costs</u>: ADR is a complex and expensive process. The cost of developing and implementing an ADR system can be significant. Difficulties in tracking and identifying space debris.

<u>Collision Risk</u>: There is always a risk of collision between the ADR system and other objects in orbit. This risk must be carefully managed.

Despite the challenges, the ADR market shows promise. As the dangers of space debris become more well known, the demand for ADR services is likely to increase. This will lead to the development of new technologies and market growth.

11. Synthesis from the Interviews

The following content is an abstract nut-shell synthesis of interviews conducted to substantiate the role of circular economy in the current commercial arena. The interviews were one-to-one questionnaire type in which the participants were given a prior slot for their preparation of the role of the candidate. These questions were designed in such a way that to reflect the basic understanding and elucidation of the idea – circular economy.

11.1 About the interview candidates

Mrs. Sandra SASSONNE, Airbus Commercial, Toulouse, France

She is an Environment officer, who is leading the Aircraft end-of-life multifunctional team within Airbus commercial, Toulouse, France. She is also leading the strategic company development regarding circular economy. Currently, she is part of the aviation environment road mapping corporate office and has been dealing extensively with circular economic concepts over the past three years.

Mr. Frank KOCH, Entrepreneur - #TheMoon, Germany

He is an entrepreneur at #TheMoon consortium and a physicist. He worked for IT development at Microsoft for 14 years. Followed by his unique career path, he founded the orbit recycling company in Germany. Currently, he and his company are working towards collection of space debris and smart lunar space industry.

11.2 A nutshell review- Mrs. Sandra

The adoption of circular economy principles in the aviation and space industries is a growing trend. It is necessary to minimize environmental impact, reduce CO2 emissions, and find alternative sources of materials.

The adoption of circular economy principles in the aviation industry is still in its early stages, but there is a clear trend towards reducing waste and maximizing the value of end-of-life materials. The commercial aviation industry is by its nature circular, as products are designed to have a long lifespan and repairs and maintenance are common. There is also a focus on reducing weight during the production process, and on managing end-of-life products to minimize environmental impact.

A new emerging principle is to value end-of-life materials, as these materials are often scarce and valuable. One way to do this is to find alternative sources of metals, such as from end-of-life products.

Another emerging trend is to collaborate with other industries to find new uses for high-quality materials. This would create an outbound flow of materials from the aviation industry to other industries.

The commercial aviation industry is still learning from other industries that are more advanced in circular economy practices. These industries often have simpler products with fewer different types of materials, which makes it easier to implement circular economy principles.

The adoption of circular economy principles in the space industry is being hindered by several factors, including the prioritization of reducing greenhouse gas emissions, the lack of alternative sources of materials, and political changes.

The space industry is under pressure to reduce its greenhouse gas emissions. This is due to the increasing focus on climate change mitigation, as well as the growing political will to address this issue. As a result, the space industry is focusing its efforts on reducing emissions, rather than on finding alternative sources of materials.

Another factor hindering the adoption of circular economy principles in the space industry is the lack of alternative sources of materials. The space industry uses a variety of materials, many of which are scarce and difficult to source. This makes it difficult to find ways to reduce waste and maximize the value of end-of-life materials.

Finally, political changes are also hindering the adoption of circular economy principles in the space industry. In recent years, there have been several changes in the regulatory landscape, which have made it more difficult for the space industry to operate. These changes have made it more difficult for the industry to invest in circular economy initiatives.

Despite these challenges, there are several opportunities for the space industry to adopt circular economy principles. These opportunities include:

Collaborating with other industries: The space industry can collaborate with other industries that are more advanced in circular economy practices. This would allow the space industry to learn from other industries and to adopt their best practices.

Investing in research and development: The space industry can invest in research and development to develop new technologies that can help to reduce waste and maximize the value of end-of-life materials.

Working with governments: The space industry can work with governments to develop policies that support the adoption of circular economy principles.

The main concern for the adoption of circular economy principles in the aviation and space industries is safety. The aviation and space industries are highly regulated, and safety is paramount. When considering the adoption of circular economy principles, the first question that comes to mind is whether it is possible to maintain the same level of safety when using recycled materials or second-hand parts.

There are several ways to address this concern. One way is to develop new testing and certification procedures that can ensure the safety of recycled materials and second-hand parts. Another way is to develop new technologies that can make recycled materials and second-hand parts more reliable.

The aviation and space industries are already taking steps to address the safety concerns associated with circular economy principles. For example, the European Union is developing new regulations that will require companies to recycle critical materials.

The adoption of circular economy principles in aviation and space education is essential to ensure that future generations are prepared to address the environmental challenges facing these industries.

Circular economy principles offer a potential solution to the environmental challenges facing the aviation and space industries, such as greenhouse gas emissions, resource depletion, and waste generation. However, the adoption of these principles requires a change in mindset and approach to education.

Traditionally, aviation and space education has focused on the production of new products and technologies. This approach has led to the creation of a linear economy, in which materials are extracted, used, and then discarded. Circular economy principles, on the other hand, promote the reuse, remanufacture, and recycling of materials.

11.3 A nutshell review- Mr. Frank

The space industry is currently in a linear economy, where materials are used and then discarded. This is not sustainable, as it leads to the accumulation of space debris. A circular economy for space would focus on reusing, recycling, and repairing materials. This would help to reduce the amount of space debris and make the space industry more sustainable.

There are several challenges to implementing a circular economy for space. One challenge is the lack of regulations. Currently, there is no international law that requires spacefaring nations to remove their space debris. Another challenge is the high cost of recycling materials in space. The space environment is harsh, and it can be difficult and expensive to process materials in space.

Despite these challenges, there are several opportunities for a circular economy for space. One opportunity is the development of new technologies that make it easier to recycle materials in space. Another opportunity is the creation of new markets for recycled materials in space.

Overall, a circular economy for space is a promising way to make the space industry more sustainable. By reusing, recycling, and repairing materials, the space industry can reduce the amount of space debris and protect the environment.

The space industry is currently in a linear economy, where materials are used and then discarded. This is not sustainable, as it leads to the accumulation of space debris. A circular economy for space would focus on reusing, recycling, and repairing materials. This would help to reduce the amount of space debris and make the space industry more sustainable.

One of the challenges of implementing a circular economy for space is the high cost of recycling materials in space. The space environment is harsh, and it can be difficult and expensive to process materials in space. However, there are several opportunities for a circular economy for space. One opportunity is the development of new technologies that make it easier to recycle materials in space. Another opportunity is the creation of new markets for recycled materials in space.

There is a project to develop a process to retrieve aluminium from moondust. This is a challenging task, but it could have a significant impact on the sustainability of the space industry. If aluminium could be easily retrieved from moondust, it could be used to build new satellites and other spacecraft, reducing the need to launch new materials from Earth.

It is evident that there is a great deal of importance of designing satellites with the idea of a second life in mind. This means designing satellites that are easy to disassemble and reuse, rather than simply being discarded after their initial mission. By designing satellites in this way, we can reduce the amount of space debris and make the space industry more sustainable.

Here are some specific key challenges and opportunities for implementing a circular economy framework in the space sector:

Challenges:

High cost of recycling materials in space: The space environment is harsh, and it can be difficult and expensive to process materials in space.

Technical challenges: There are several technical challenges to recycling materials in space, such as the need for specialized equipment and the difficulty of transporting materials.

Lack of regulations: There is currently no international law that requires spacefaring nations to recycle their space debris. This makes it difficult to enforce a circular economy for space.

Opportunities:

Development of new technologies: The development of new technologies, such as autonomous robots and 3D printing, could make it easier and more cost-effective to recycle materials in space.

Creation of new markets for recycled materials in space: The creation of new markets for recycled materials in space could provide an economic incentive for companies to recycle.

Increased public awareness: Increased public awareness of the problem of space debris could put pressure on governments and businesses to adopt a circular economy for space.

12. Conclusion

The circular economy for space is a promising approach to make space exploration more sustainable. It is a production and consumption model that aims to reduce waste and pollution by using products and materials for as long as possible. This may be true for the space sector, which is a large resource consumer.

By implementing the principles of a circular economy, the space sector can reduce its impact on the environment and become more sustainable like Reuse and refurbishment of spacecraft and their components, Recycling materials from spacecraft and other space debris, Design spacecraft and their components to be more modular and easier to disassemble and reassemble, Use of bio-based materials that can be composted or biodegraded after use and importantly. Development of new technologies for the extraction and use of space resources.

12.1 Recommandations

- Investment towards research labs specific to circular economy for space to incubate and develop microbes to innovate and develop sustainable technologies which will be a boon for life extension of astronauts for future long-term space missions.
- Investment towards research and development through joint ventures between Government organisations and private space sectors boost the adaptability and applicability of circular economy in space.
- The concept of circular economy in space needs to be emphasized and followed through a wide spectrum of educational forums, private space sectors, Government and private space startups with proper channelized brainstorming and exchange of technology.
- More supportive and dedicated funding towards active space debris removal could be a promising and safe future for all space missions henceforth.
- Also, there is a profound need for the development of intuitive and diligent business models which will shape and support the Space mission's developments, design and development of satellites which will be oriented towards circular economy.
- Finally, the implementation of circular economy must be prioritized over current linear economic model of space sector in a motive to bring more sustainable space missions.

With the above forementioned recommendations, also with recent substantial growths and opportunities towards circular economy for space, the findings of this research conclude that, in next 10 years there will be a great leap of paradigm shift in the way the space missions designed and present a promising and sustainable future for all.

Literature Review

1. Ana de Jesus, Sandro Mendonça (2017), Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy: ELSEVIER, http://dx.doi.org/10.1016/j.ecolecon.2017.08.001
2. Angie Silva, Michele Rosano, Laura Stocker, Leen Gorissen (2017), From waste to sustainable materials management: Three case studies of the transition journey, Waste Management, https://doi.org/10.1016/j.wasman.2016.11.038.
3. Anttonen, Markku & Lammi, Minna & Mykkänen, Juri & Repo, Petteri. (2018). Circular Economy in the Triple Helix of Innovation Systems. Sustainability. http://dx.doi.org/10.3390/su10082646
4. Arnold Tukker (2015), Product services for a resource-efficient and circular economy – a review, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2013.11.049.
5. Barbaroux, P., & Dos Santos Paulino, V. (2022). Why do motives matter? A demand-based view of the dynamics of a complex products and systems (CoPS) industry. Journal of Evolutionary Economics. https://doi.org/10.1007/s00191-022-00788-1
6. Barrera Saavedra, Yovana & Iritani, Diego & Pavan, Ana Laura & Ometto, Aldo. (2017). Theoretical contribution of industrial ecology to circular economy. Journal of Cleaner Production. http://dx.doi.org/10.1016/j.jclepro.2017.09.260
7. Ben Purvis, Dilay Celebi, Mario Pansera (2023). A framework for a responsible circular economy: ELSEVIER. https://doi.org/10.1016/j.jclepro.2023.136679
8. Berkel, Rene. (2007). Cleaner production and eco-efficiency initiatives in Western Australia 1996–2004. Journal of Cleaner Production. http://dx.doi.org/10.1016/j.jclepro.2006.06.012
9. Blomsma, Fenna & Brennan, Geraldine. (2017). The Emergence of Circular Economy - A New Framing Around Prolonging Resource Productivity. Journal of Industrial Ecology. http://dx.doi.org/10.1111/jiec.12603
10. Bocken, Nancy & Pauw, Ingrid & Bakker, C.A. & van der Grinten, Bram. (2016). Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 1015. https://doi.org/10.1080/21681015.2016.1172124
11. Buren, Nicole & Demmers, Marjolein & Heijden, Robert & Witlox, Frank. (2016). Towards a Circular Economy: The Role of Dutch Logistics Industries and Governments. Sustainability. http://dx.doi.org/10.3390/su8070647
12. Chantal Ykman-Couvreur, Philipp A. Hartmann, Gianluca Palermo, Fabien Colas-Bigey, Laurent San (2012), Run-time Resource Management based on Design Space Exploration: ACM Digital Library, https://dl.acm.org/doi/10.1145/2380445.2380530
13. Chiara Farné Fratini, Susse Georg, Michael Søgaard Jørgensen, Exploring circular economy imaginaries in European cities: a research agenda for the governance of urban sustainability transitions, Journal of Cleaner Production (2019), https://www.sciencedirect.com/science/article/abs/pii/S0959652619312806
14. Chizaryfard, Armaghan & Trucco, Paolo & Nuur, Cali. (2021). The transformation to a circular economy: framing an evolutionary view. Journal of Evolutionary Economics. https://doi.org/10.1007/s00191-020-00709-0
15. Christina M. Bidmon, Sebastian F. Knab, The three roles of business models in societal transitions: New linkages between business model and transition research, Journal of Cleaner Production (2017), https://doi.org/10.1016/j.jclepro.2017.12.198

16. Claudi Marcela Betancourt Morales, Jhon Wilder Zartha Sossa, (2020). Circular economy in Latin America: A systematic literature review: Business Strategy and Environment, https://doi.org/10.1002/bse.2515.
17. Cloitre, A., Dos Santos Paulino, V., & Theodoraki, C. (2022). The quadruple/quintuple helix model in entrepreneurial ecosystems: An institutional perspective on the space case study. R&D Management. https://doi.org/10.1111/radm.12547
18. David Peck, Prabhu Kandachar, Erik Tempelman (2015), Critical materials from a product design perspective, Materials & Design (1980-2015), https://doi.org/10.1016/j.matdes.2014.08.042.
19. Davide Basile, Idiano D'Adamo, Valerio Goretti & Paolo Rosa (2023): Digitalizing Circular Economy through Blockchains: The Blockchain Circular Economy Index, Journal of Industrial and Production Engineering, https://www.tandfonline.com/doi/full/10.1080/21681015.2023.2173317
20. Deborah Andrews (2015), The circular economy, design thinking and education for sustainability: Local Economy, https://doi.org/10.1177/0269094215578226
21. Denise Reike, Walter J.V. Vermeulen, Sjors Witjes (2018), The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options, Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2017.08.027.
22. Dieter Schuch, Jakob Lederer, Johann Fellner, Christoph Scharff (2023), Separate collection rates for plastic packaging in Austria – A regional analysis taking collection systems and urbanization into account, Waste Management, https://doi.org/10.1016/j.wasman.2022.09.023.
23. Dos Santos Paulino, V. (2020). Innovation Trends in the Space Industry. Wiley-ISTE.
24. Dos Santos Paulino, V., & Gudmundsson, S. V. (2021). Market Diffusion of Industrial Products and Regulatory Barriers to Adoption: The Case of Satellites. Journal of Innovation Economics & Management. https://doi.org/10.3917/jie.pr1.0097
25. Dos Santos Paulino, V., & Pulsiri, N. (2022). Safeguarding Earth and space's environment: Issues and trends towards sustainable development. International Journal of Technology Management & Sustainable Development. https://doi.org/10.1386/tmsd_00063_1
26. Enes Ünal, Andrea Urbinati, Davide Chiaroni, (2018) "Managerial practices for designing circular economy business models: The case of an Italian SME in the office supply industry", Journal of Manufacturing Technology Management, https://doi.org/10.1108/JMTM-02-2018-0061
27. Erinn G. Ryen, Gabrielle Gaustad, Callie W. Babbitt, Gregory Babbitt (2018), Ecological foraging models as inspiration for optimized recycling systems in the circular economy, Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2017.08.006.
28. Fellner, Johann & Lederer, Jakob & Scharff, Christoph & Laner, David. (2017). Present Potentials and Limitations of a Circular Economy with Respect to Primary Raw Material
29. Demand: Present Potentials and Limitations of a Circular Economy. Journal of Industrial Ecology. http://dx.doi.org/10.1111/jiec.12582
30. Fenna Blomsma and Geraldine Brennan (2017) The Emergence of Circular Economy- A New Framing Around Prolonging Resource Productivity: Journal of Industrial Ecology, https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12603
31. Frank W. Geels (2011), The multi-level perspective on sustainability transitions: Responses to seven criticisms, Environmental Innovation and Societal Transitions, volume 1, Issue 1, Pages 24-40, ISSN 2210-4224, https://doi.org/10.1016/j.eist.2011.02.002.
32. G. Mariani, V. -M. Sima, G. Palermo, V. Zaccaria, C. Silvano and K. Bertels (2012), "Using multi-objective design space exploration to enable run-time resource management for reconfigurable architectures," 2012 Design, Automation & Test in Europe Conference & Exhibition (DATE), Dresden, Germany, https://doi.org/10.1109/DATE.2012.6176578

33. Gabrielle Gaustad, Mark Krystofik, Michele Bustamante, Kedar Badami (2018), Circular economy strategies for mitigating critical material supply issues, resources, Conservation and Recycling, Volume 135, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2017.08.002.
34. Grundmann, V., Bilitewski, B., Zehm, A. et al (2013). Risk-based management of chemicals and products in a circular economy at a global scale- Impacts of the FP7 funded project RISKCYCLE. Environ Sci Eur 25, 14. https://doi.org/10.1186/2190-4715-25-14
35. Gureva, Maria. (2020). Conservation and rational use of natural resources: methods of circular economy assessment. IOP Conference Series: Materials Science and Engineering. 828. 012010. http://dx.doi.org/10.1088/1757-899X/828/1/012010
36. H. Winkler (2011), Closed-loop production systems—A sustainable supply chain approach, CIRP Journal of Manufacturing Science and Technology, https://doi.org/10.1016/j.cirpj.2011.05.001.
37. Herman I. Stål, Herve Corvellec, A Decoupling perspective on Circular Business Model implementation: illustrations from Swedish apparel, Journal of Cleaner Production (2017), https://www.sciencedirect.com/science/article/abs/pii/S0959652617322618
38. Hobson, Kersty & Lynch, Nicholas. (2016). Diversifying and de-growing the circular economy: Radical social transformation in a resource-scarce world. Futures. http://dx.doi.org/10.1016/j.futures.2016.05.012
39. Jackson, Melissa & Lederwasch, Aleta & Giurco, Damien. (2014). Transitions in Theory and Practice: Managing Metals in the Circular Economy. Resources. http://dx.doi.org/10.3390/resources3030516
40. James A. Blake, (2022), Looking out for a sustainable space: RAS Journals, https://arxiv.org/abs/2202.06994
41. Janardhan Rao Doppa (2018), Autonomous Design Space Exploration of Computing Systems for Sustainability: Opportunities and Challenges: IEEE Xplore, https://ieeexplore.ieee.org/document/8786182
42. Jim Harta, Katherine Adamsb, Jannik Giesekamc, Danielle Densley Tingleyd, Francesco Pomponia (2019). Barriers and drivers in a circular economy: the case of the built environment: ELSEVIER. https://www.sciencedirect.com/science/article/pii/S2212827118312940
43. Johannes Daae, Lucy Chamberlin & Casper Boks (2018) Dimensions of Behaviour Change in the context of Designing for a Circular Economy, The Design Journal, 21:4, https://doi.org/10.1080/14606925.2018.1468003
44. Jose Garcia-Quevedo, Elisenda Jové-Llopis, Ester Martinez-Ros (2020). Barriers to the Circular Economy in European small and medium firms: Business Strategy and the Environment. https://onlinelibrary.wiley.com/doi/10.1002/bse.2513
45. Jouni Korhonen, Antero Honkasalo, Jyri Seppälä (2018), Circular Economy: The Concept and its Limitations, Ecological Economics, https://doi.org/10.1016/j.ecolecon.2017.06.041.
46. K. Winans, A. Kendall, H. Deng (2017), The history and current applications of the circular economy concept, Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2016.09.123.
47. Karin Bradley & Ola Persson (2022) Community repair in the circular economy – fixing more than stuff, Local Environment, https://www.tandfonline.com/doi/full/10.1080/13549839.2022.2041580
48. Larysa Soroka (2020), Modern Challenges to Establishing Global Law on Sustainable Development of Space Activities: Advanced Space Law, Volume 6, 64-71. https://doi.org/10.29202/asl/6/7
49. Lewandowski, Mateusz. (2016). Designing the Business Models for Circular Economy—Towards the Conceptual Framework. Sustainability. http://dx.doi.org/10.3390/su8010043

50. Li-Heng Chen, Peiying Hung, Hwong-wen Ma (2020), Integrating circular business models and development tools in the circular economy transition process: A firm-level framework: Business Strategy and the Environment, https://doi.org/10.1002/bse.2477
51. Lothar Reh (2013), Process engineering in circular economy, Particuology, https://doi.org/10.1016/j.partic.2012.11.001.
52. Lucken, Romain & Hubert, N & Giolito, D. (2017). Systematic space debris collection using Cubesat constellation Share My Space, Orbit cleaning and Space Debris Recycling. http://dx.doi.org/10.13009/EUCASS2017-678
53. M.M. Pérez-Martínez, C. Carrillo, J. Rodeiro-Iglesias, B. Soto (2021), Life cycle assessment of repurposed waste electric and electronic equipment in comparison with original equipment, Sustainable Production and Consumption, https://doi.org/10.1016/j.spc.2021.03.017.
54. Madsen, Jan & Stidsen, Thomas & Kjaerulf, Peter & Mahadevan, Shankar. (2006). Multi-Objective Design Space Exploration of Embedded System Platforms. International Federation for
55. Information Processing Digital Library; From Model-Driven Design to Resource Management for Distributed Embedded Systems. 225. 185-194. http://dx.doi.org/10.1007/978-0-387-39362-9_20
56. Maria Concepción Peñate-Valentín, María del Carmen Sánchez-Carreira, Ángeles Pereira (2021), The promotion of innovative service business models through public procurement. An analysis of Energy Service Companies in Spain, Sustainable Production and Consumption, https://doi.org/10.1016/j.spc.2021.04.028.
57. Maria Lucas-Rhimbassen, Cristiana Santos, George Antony Long, Lucien Rapp, 8th European Conference for Aeronautics and Space Sciences (EUCASS)
58. Masi, Donato & Day, Steven & Godsell, Janet. (2017). Supply Chain Configurations in the Circular Economy: A Systematic Literature Review. Sustainability. http://dx.doi.org/10.3390/su9091602
59. Mathews, John & Tan, Hao. (2011). Progress Toward a Circular Economy in China. Journal of Industrial Ecology. 15. http://dx.doi.org/10.1111/j.1530-9290.2011.00332.x
60. Mikhail V. Shubov (2021), Feasibility Study for Multiply Reusable Space Launch System: Arxiv https://doi.org/10.48550/arXiv.2107.13513
61. Milios, Leonidas (2018), Advancing to a Circular Economy: three essential ingredients for a comprehensive policy mix, Sustainability Science, Milios 2018, https://doi.org/10.1007/s11625-017-0502-9
62. Mohammed Haneef Abdul Nasir, Andrea Genovese, Adolf A. Acquaye, S.C.L. Koh, Fred Yamoah (2017), Comparing linear and circular supply chains: A case study from the construction industry, International Journal of Production Economics, https://doi.org/10.1016/j.ijpe.2016.06.008.
63. Mônica Cavalcanti Sá de Abreu, Domenico Ceglia (2018), On the implementation of a circular economy: The role of institutional capacity-building through industrial symbiosis, Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2018.07.001.
64. Nancy M. P. Bocken, Elsa A. Olivetti, Jonathan M. Cullen, Jose Potting, Reid Lifse (2017), Taking the Circularity to the Next Level- A Special Issue on the Circular Economy: Yale University, https://environment.yale.edu/bibcite/reference/3147
65. Neeraj C. Hanumante, Yogendra Shastri, Andrew Hoadley (2019), Assessment of circular economy for global sustainability using an integrated mode: ELSEVIER, https://doi.org/10.1016/j.resconrec.2019.104460
66. Ogunmakinde, Olabode. (2019). A Review of Circular Economy Development Models in China, Germany, and Japan. Recycling. http://dx.doi.org/10.3390/recycling4030027

67. Owais Khan, Tiberio Daddi, Fabio Iraldo (2019), Microfoundations of dynamic capabilities: Insights from circular economy business cases: Business Strategy and Environment, https://doi.org/10.1002/bse.2447
68. Paolo Rosa, Claudio Sassanelli, Sergio Terzi, (2019). Towards Circular Business Models: A systematic literature review on classification frameworks and archetypes, Journal of Cleaner Production https://doi.org/10.1016/j.jclepro.2019.117696
69. Patrizia Ghisellini, Catia Cialani, Sergio Ulgiati (2016), A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, Journal of Cleaner Production, Volume 114, Pages 11-32, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2015.09.007.
70. Prieto-Sandoval, Vanessa & Jaca, Carmen & Ormazabal, Marta. (2018). Towards a consensus on the circular economy. Journal of Cleaner Production. http://dx.doi.org/10.1016/j.jclepro.2017.12.224
71. Ramani, Karthik & Ramanujan, Devarajan & Bernstein, William & Zhao, Fu & Sutherland, John & Handwerker, C. & Choi, Jun-Ki & Kim, Harrison & Thurston, Deborah. (2010). Integrated Sustainable Life Cycle Design: A Review. Journal of Mechanical Design. http://dx.doi.org/10.1115/1.4002308
72. Rannveig Edda Hjaltadóttir & Paula Hild (2021), Circular Economy in the building industry European policy and local practices, European Planning Studies, https://doi.org/10.1080/09654313.2021.1904838
73. Regina Frei, Lisa Jack, Sally-Ann Krzyzaniak, (2020), Sustainable reverse supply chains and circular economy in multichannel retail returns: Business Strategy and the Environment, https://doi.org/10.1002/bse.2479
74. Remi Elzinga, Denise Reike, Simona O. Negro, Wouter P.C. Boon (2020), Consumer acceptance of circular business models: ELSEVIER, https://doi.org/10.1016/j.jclepro.2020.119988
75. Remi Elzinga, Denise Reike, Simona O. Negro, Wouter P.C. Boon (2020), Consumer acceptance of circular business models, Journal of Cleaner Production, volume 254, 119988, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2020.119988.
76. Rizos, Vasileios & Behrens, Arno & Gaast, W. & Hofman, Erwin & Ioannou, Anastasia & Kafyeke, Terri & Flamos, Alexandros & RINALDI, Roberto & Papadelis, Sotiris & Hirschnitz-Garbers, Martin & Topi, Corrado. (2016). Implementation of Circular Economy Business Models by Small and Medium-Sized Enterprises (SMEs): Barriers and Enablers. Sustainability. http://dx.doi.org/10.3390/su8111212
77. Ryan Leonard, & Ian D.Williams (2022). Viability of a circular economy for space debris: ELSEVIER. https://doi.org/10.1016/j.wasman.2022.10.024
78. Sakai, Shin-ichi & Yoshida, Hideto & Hirai, Yasuhiro & Asari, Misuzu & Takigamiet et al (2011). International comparative study of 3R and waste management policy developments. Journal of Material Cycles and Waste Management. http://dx.doi.org/10.1007/s10163-011-0009-x
79. Sarah C. Greenwood, Stuart Walker, Harriet M. Baird, Rorie Parsons, Seth Mehl, Thomas L. Webb, Andrew T. Slark, Anthony J. Ryan, Rachael H. Rothman (2021), Many Happy Returns: Combining insights from the environmental and behavioural sciences to understand what is required to make reusable packaging mainstream, Sustainable Production and Consumption, https://doi.org/10.1016/j.spc.2021.03.022.
80. Sherif Kamal, Ahmed Gaber, Farouk El-Baz (2021) An integrated design for collecting and recycling of space debris: Research Square, https://doi.org/10.21203/rs.3.rs-647907/v1
81. Shu-Yuan Pan, Michael Alex Du, I-Te Huang, I-Hung Liu, E-E Chang, Pen-Chi Chiang (2015), Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2015.06.124.

82. Silvia Bobba, Fabrice Mathieux, Fulvio Ardente, Gian Andrea Blengini, Maria Anna Cusenza, Andreas Podias, Andreas Pfrang (2018), Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows: ELSEVIER, https://doi.org/10.1016/j.est.2018.07.008
83. Stefania Paladini, Krish Saha, Xavier Pierron, Sustainable space for a sustainable Earth? Circular economy insights from the space sector, Journal of Environmental Management, 2021, https://doi.org/10.1016/j.jenvman.2021.112511.
84. Steven Kane Curtis (2021), Business model patterns in the sharing economy: ELSEVIER, https://doi.org/10.1016/j.spc.2021.04.009
85. Thayla T. Sousa-Zomer, Lucas Magalhães, Eduardo Zancul, Paulo A. Cauchick-Miguel (2018), Exploring the challenges for circular business implementation in manufacturing companies: An empirical investigation of a pay-per-use service provider, Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2017.10.033.
86. Tuomo Joensuu, Harry Edelman, Arto Saari (2020), Circular economy practices in the built environment, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2020.124215.
87. Van Schalkwyk, Frans & Reuter, Markus & Gutzmer, J. & Stelter, Michael. (2018). Challenges of digitalizing the circular economy: Assessment of the state-of-the-art of metallurgical carrier metal platform for lead and its associated technology elements. Journal of Cleaner Production. 186. http://dx.doi.org/10.1016/j.jclepro.2018.03.111
88. Wenting Jiao, Frank Boons (2014), Toward a research agenda for policy intervention and facilitation to enhance industrial symbiosis based on a comprehensive literature review, Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2013.12.050.
89. Yang, Mingyu & Chen, Lin & Wang, Jiangjiang & Msigwa, Goodluck & Osman, Ahmed & Fawzy, Samer & Rooney, David & Yap, Pow Seng. (2022). Circular economy strategies for combating climate change and other environmental issues. Environmental Chemistry Letters. http://dx.doi.org/10.1007/s10311-022-01499-6
90. Yo-Ann Velez Justiniano, Darla M. Goeres, Elizabeth L. Sandvik, Birthe Veno Kjellerup, Tatyana A. Sysoeva, Jacob S. Harris, Stephan Warnat, Matthew McGlennen, Christine M. Foreman, Jiseon Yang, Wenyan Li, Chelsi D. Cassilly, Katelyn Lott, Lauren E. HerrNeckar (2022), Mitigation and use of biofilms in space for the benefit of human space exploration: ELSEVIER, https://doi.org/10.1016/j.bioflm.2022.100102
91. Yuan, Zengwei & Bi, Jun & Moriguchi, Yuichi. (2008). The Circular Economy: A New Development Strategy in China. Journal of Industrial Ecology. http://dx.doi.org/10.1162/108819806775545321
92. Yuliya Kalmykova, Madumita Sadagopan, Leonardo Rosado (2018), Circular economy – From review of theories and practices to development of implementation tools, Resources, Conservation and Recycling, https://doi.org/10.1016/j.resconrec.2017.10.034.

APPENDIX

Questionnaire for the interview

- What are some key challenges and opportunities associated with implementing a circular economy framework in the space sector?
- Can you provide an overview of the concept of Circular Economy for Space and its significance in the space industry?
- From an economic standpoint, what are the potential benefits and potential barriers of adopting a circular economy model in the space sector?
- How can space debris mitigation and removal efforts contribute to the principles of circularity in space?
- What are the potential environmental benefits of adopting a circular economy approach in the space industry?
- What are some innovative approaches or concepts that you believe can revolutionize the circular economy in space?
- How do you see the future of circular economy in space evolving over the next decade? What milestones or advancements do you anticipate?
- What topic should be good to address in the thesis that we have not spoken about in the interview?