Business adaptive strategies in crisis: In the context of SpaceX and the space debris crisis

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Abstract

Title: Business adaptive strategies in crisis: In the context of SpaceX and the space debris crisis

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This master thesis examines the business adaptive strategies, SpaceX has developed to address the ever-evolving space debris crisis today and in the future. The dissertation is written in the form of a case study and aims to link theoretical management frameworks with real-life issues.

The theoretical management frameworks are presented in the research note chapter 4 and include dynamic capabilities, CSR reporting, Eco innovation and VRIO, followed by the case study in chapter 5. The case study chapter contains the theoretical part, with the demonstration of the space debris crisis, risks for space missions, risk for earth and space environment, current legal frameworks, and the business adaptive strategies of SpaceX in general as well as based on two major missions. The last chapter 6 is the teaching note, in which the theoretical frameworks of chapter 4 are linked to the business adaptive strategies of SpaceX.

The case analyzes the strategies SpaceX has developed to address the crisis, from spacecraft reusability to transparently provision of informing about current space debris positions and the space debris avoidance maneuvers SpaceX must perform. Further, SpaceX’s cost benefits due to their adaptive strategies were highlighted and compared to other space operators.

SpaceX’s premature development in sustainable space practices addressing the need for space debris mitigation will give SpaceX a recognizable competitive advantage in the future, as they are already acting above the required guidelines and can quickly react to changing legal requirements through their in-house production utilizing vertical integration.

Keywords: Space debris crisis, SpaceX, CSR, Dynamic capabilities, Agility & Adaptability, Eco innovation

Resumo

Título: Estratégias de adaptação das empresas em situações de crise: No contexto da SpaceX e da crise dos detritos espaciais

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Esta dissertação examina as estratégias de adaptação desenvolvidas pela SpaceX para fazer face à crise evolutiva dos detritos espaciais atualmente e no futuro. A dissertação compõe-se do estudo deste caso e pretende ligar quadros teóricos de gestão a questões reais quotidianas.

O enquadramento teórico apresenta-se no capítulo 4, abordando as capacidades dinâmicas, os relatórios de RSE, a eco-inovação e o VRIO. Segue-se o estudo de caso no capítulo 5, que contém a parte teórica, com a apresentação da crise dos detritos espaciais, os riscos para as missões espaciais e para o ambiente terrestre e espacial, os quadros jurídicos atuais e as estratégias de adaptação genérica empresarial da SpaceX, bem como os procedimentos em duas grandes missões. O último capítulo 6 é a nota didática, na qual os quadros teóricos do capítulo 4 são associados às estratégias de adaptação empresarial da SpaceX.

O caso analisa as estratégias que a SpaceX desenvolveu para enfrentar a crise, desde a reutilização de naves espaciais até ao fornecimento transparente de informações sobre a localização de detritos espaciais e as manobras a efetuar para os evitar. Além disso, os benefícios de custos devido às suas estratégias adaptativas foram destacados e comparados com os de outros operadores espaciais.

O desenvolvimento prematuro da SpaceX de práticas sustentáveis de redução do problema do lixo espacial dar-lhe-á uma vantagem competitiva futura, uma vez que está já a agir além das diretrizes presentes e pode reagir rapidamente a qualquer alteração de requisitos legais através de produção interna, utilizando a integração vertical.

Palavras-chave: Crise dos detritos espaciais, SpaceX, RSE, Capacidades dinâmicas, Agilidade e adaptabilidade, Eco-inovação

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2 List of abbreviations

LEO – Low Earth Orbit

GEO – Geostationary Orbit

PES – Proactive Environmental Strategy

ECHA – European Chemicals Agency

ISS – International Space Station

SSA – Space Situational Awareness

USAF – US Air Force

ADR – Active Debris Removal

LODR – Laser Optical System to Remove Low Earth Space Debris

ODMSP – Orbital Debris Mitigation Standard Practices

ESA – European Space Agency

FCC – Federal Communications Commissions

TPL – third-party liability

SSR – Space Sustainability Rating

VTVL – vertical takeoff, vertical landing

NPV – Net Present Value

CSR – Corporate Social Responsibility

NASA – National Aeronautics and Space Administration

IADC – Inter-Agency Space Debris Coordination Committee

GHG – Greenhouse Gas

3 Introduction & Methodology

The number of nations actively engaging in space exploration missions is constantly increasing. The consequence is a significant accumulation of space objects in the diverse orbits, which includes active objects in operational service, but also defunct satellites, various stages of rockets and fragments resulting from collisions between space crafts. The problem of space debris is an ever-evolving crisis and currently poses a threat to earth and orbital environment as well as to space missions but will have far-reaching implications in the future. One of the greatest risks arises from collision of space objects, as such collisions create thousands and thousands of small fragments in centimeter range, which can cause immense damage to space crafts due to the high speeds in orbit. A collision with these small fragments could cause a complete failure of a satellite, which is a vicious circle, as new space debris is constantly being created.

This master's thesis deals with the space debris crisis and SpaceX's business adaptive strategies to address and mitigate this crisis. SpaceX is an innovative space manufacturing, space transportation and space service providing company based in the United States, known for its CEO and founder Elon Musk. The company attracted public attention in 2015 with the first use of a reusable booster of the Falcon 9 rocket, which returned to earth after launch and was able to land vertically, making it possible to reuse this booster. SpaceX is at the forefront of sustainable space utilization in the space industry, which they demonstrate through missions such as Starlink mega constellation and its according sustainable strategies, as well as the reusability of rocket boosters. During this master thesis, SpaceX's various business adaptive strategies to mitigate the space debris problem are presented and analyzed. Combining space regulations, management strategies and the environmental impact of space debris, the need of future adaptation and adjustments of spacer operator strategies for space missions are clearly demonstrated.

The master thesis is based on a comprehensive literature review, relying exclusively on secondary sources, such as internal company reports, scientific articles, and prevailing public interviews with SpaceX management.

4 Research note

4.1 Dynamic Capabilities

Dynamic capabilities can be seen as the ability of a firm to change their internal and external competences in a business world of rapidly changing environments. This allows companies to accomplish innovative forms of competitive advantage (Teece, Pisano and Shuen, 2009). In general dynamic capabilities can be seen as transformation of common capabilities over time (Vu, 2020). A further definition of dynamic capabilities is defined by Eisenhardt and Martin in (Eisenhardt and Martin, 2000) where dynamic capabilities are only processes to use, to reconfigure, to release and to gain resources to fulfil or even change the market.

Two major aspects of dynamic capabilities need to be analyzed in this context. First, the word dynamic, which refers to a company's ability to update its strategies through external influences such as rapid technological changes or to cope with future competitors. Capabilities on the other hand is one of the main roles in strategic management. It is how companies can adapt and reconfigure internal capabilities, external organizational resources, and practical competencies to meet the demands that the business world places on them due to rapid change (Teece, Pisano and Shuen, 2009).

The remaining sections in this chapter present several dynamic capabilities that fit SpaceX's business model and its ability to quickly adapt to changes in the space industry in regards to space debris.

Innovative Capabilities and technological development

As (Vu, 2020) states, firms can decrease inefficiencies and increase performance due to usage of innovative capabilities. Innovative capabilities is generally understood as a company's potential to develop new inventions or products that relate to innovative procedures and processes with connecting a company’s resources and capabilities to a competitive advantage on the product market (Wang and Ahmed, 2007).

Adaptability and agility

Organizational agility as dynamic capability is the power to quickly react to unexpected changes in product and service demand to accomplish competitive advantage (Singh *et al.*, 2013). Given (Appelbaum *et al.*, 2017) due to a rise strength of competition and the rate of innovations, which has been adopted, companies need to be able to constantly change their strategies to sustain competitive advantage. However, it should be mentioned that companies shouldn't alter their strategic approach for the sake of agile change, rather companies should not lose focus on their core competencies (Appelbaum *et al.*, 2017).

Adaptability on the other hand is the competence of a company to identify alterations and recognize opportunities in a fast changing business world (Schulze and Pinkow, 2020). Companies need to asses' new opportunities and grasp benefits from these opportunities to reconfigure their organizational structure to gain a competitive advantage (David J. Teece; Gary Pisano; Amy Shuen, 1997).

Environmental Responsibility and Reputation Management:

Environmental responsibility as a dynamic capability plays a crucial role in the business world of any existing industry. Environmental damage can be avoided by reducing greenhouse gas emissions or minimizing waste generation using reusable materials. These capabilities can lead to a greater customer loyalty plus a more advantageously image in the international markets (Karia, 2022). Additionally, a further environmental dynamic capability like eco innovation must be mentioned in this context. Eco innovation will be discussed as a stand-alone capability in the following chapter 4.2.

4.2 Eco Innovation

Eco-innovation is the ability of an organization to design and adapt its business processes and organizational methods in ways that benefit the environment regardless of whether they are intentional or unintentional (Cheng, Yang and Sheu, 2014). Increasing pressure from governments regarding the sustainability of production is forcing companies to integrate environmental innovation programs into their business strategy (Dangelico and Pujari, 2010). Generally, the eco innovation capability can be subdivided in three categories, the eco process innovation, the eco product innovation and the eco organizational innovation. The eco process innovation refers to the strategy of implementing new production systems to lower the impact on the environment. Eco product innovation, on the other hand, involves the development of new and improved products, for example through new technologies and materials. Here, the ecological impact relates less to the production of a product and more to the ecological impact during a product life cycle. Closing, eco organizational innovation stands for updating management processes through new and ecological business practices, like eco training programs, eco product design programs or building internal teams which deal with eco issues (Cheng, Yang and Sheu, 2014).

4.3 VRIO Framework

The VRIO – framework was developed by Jay Barney in 1991 in the Journal Academy of Management Executive. VRIO stands for value, rareness, imitability & organization and is a management framework for analyzing a company's capabilities to gain and sustain competitive advantage. The VRIO framework is part of the Resourced-Based View (RBV) framework, which describes the link of the internal qualities with the external performance.

Do a company's resources create value to achieve competitive advantage?

Companies must exploit opportunities and risks to gain and maintain a competitive advantage. Furthermore, companies must be able to combine their internal capabilities with external opportunities to utilize their resources profitably. Resources are valuable, when a company is able to implement strategies to increase efficiency and effectiveness.

How rare are the resources compared to the competition?

As soon as valuable resources and capabilities are equally distributed on the market, competitive parity is created and therefore does not provide any competitive advantage. Managers therefore need to ask themselves how many companies are already using this capability or resource to achieve rareness of the resource.

How easy can the value of a company been imitated by the competition?

If the resources of a company are rare and valuable plus represents cost disadvantages for the competitors who want to imitate them, the third criterion of the VRIO framework is fulfilled.

Can the company organize the resources to gain value?

As the resource itself does not yet generate any value, it must be organized by the company to do so. If resources are therefore valuable, rare, difficult to imitate and organized in a structured way, this leads to a long-term competitive advantage.

In conclusion, by fulfilling all four criteria of the VRIO framework, an increasing or equal competitive advantage can prevail.

The information in chapter 4.3 was taken from the following sources (Barney, 1995), (Barney, 1991) and (Astawa, 2022).

4.4 Corporate Social Responsibility (CSR) Reporting

CSR reporting is a tool and framework companies can apply to provide information on economic, environmental and social performances to their stakeholders and public in order to provide transparency to ensure a sustainable development of the company (Guthrie and Yongvanich, 2004). CSR also demands that the sole focus on pure profit need be set aside, and a broader spectrum of social relations to be focused on. In this context, it is crucial to apply a transparent communication tool for correspondence with customers and public in relation to CSR activities. A transparent exchange with the public promotes reputation, prestige, and a demonstration of effective, efficient, and attentive management of resources. Through a constant exchange of a company's CSR practices with the outside world, leads to an increase in transparency, the involvement of stakeholders and an overarching exchange with governments and non-profit organizations. An open CSR reporting culture can also be used to evaluate and compare companies' CSR strategies. Information on companies' CSR activities is recorded in the CSR report, which can help to form a socio-ecological management approach to derive future lines of action and opportunities to maintain and increase competitive advantages. The CSR report must fulfill four main criteria, which are credibility, completeness, informative value and appropriate form. (Moravcikova, Stefanikova and Rypakova, 2015). To conclude the topic of CSR reporting, the term "greenwashing" should not be absent. The phenomenon of greenwashing is a direct result of the development of CSR, as customers and society have an ever-increasing demand for environmentally friendly products and services, whereby companies want to attract more customers through misinformation and improve their corporate image and acquire new investors (WOLNIAK, 2016). This is why CSR reporting is particularly susceptible to greenwashing (William and Chandler, 2011).

5 Case study

5.1 Introduction to the Industry and Company

SpaceX is one of the largest private space operators in the United States located in Hawthorne, California. Elon Musk, known for Tesla, founded SpaceX in 2002 and has been playing since then a playing leading role in the sustainable transformation of the space industry. SpaceX's reusable rocket booster made the company even better known worldwide in 2015 with the successful landing of the booster and in 2017 with the first relaunch. That year, the company managed to successfully relaunch a first stage that had flown earlier that year. SpaceX was not the first space company utilizing reusable space objects if you think of the American space shuttle program, which was designed to launch cargo and astronauts to the international space station (ISS) and operated between 1982 and 2010 (Reddy, 2018).

SpaceX is valued with around $150 billion in a recent employee stock sale, which corresponds to the same enterprise value of Intel or Walt Disney. Between January and March of this year, SpaceX generated a profit of $55 million on revenues of $1.5 billion. This allowed SpaceX to return to profit after the previous years were characterized by losses, with $559 million in 2022 e.g. (Reuters, 2023).

The American space industry was generating around $38 billion in the year 2016, which represented 2% of the GDP in the US (Whealan George, 2019). Morgan Stanley calculated, that until the year 2040 the global space industry will generate up to $1 trillion with a steady growth rate (Stanley, 2020).

5.1.1 Projects of SpaceX

With the reusable rocket "Falcon 9", which had its first launch in 2010, 31 launches were carried out in 2021 alone. After launch, the first stage boosters separate and return to earth to land on a platform in the sea, which was achieved for the first time in 2015. In 2021, SpaceX celebrated the 100th landing of a booster, which significantly reduces the cost of a single rocket launch and proving its functionality as it has successfully launched before (Banner, 2022). Since SpaceX's focus is on cost savings, made possible by reusability, allows them to offer a Falcon 9 launch price of $62 million dollars, well below the competition. Compared to the former Space Shuttle with launch costs of $1.6 billion and the Russian counterpart Soyuz with launch costs of $225 million, SpaceX is the market leader in the area of the cost efficient rocket launches (Chow, 2022).

The second project referred to in this context is "Starlink". Starlink is a so-called satellite mega-constellation, which offers broadband Internet thanks to many small satellites (Space X, no date). Mega constellations are communication satellites, which have grown by 50% in the last two years and (as of March 30, 2021) have reached a number of approximately 5000, which has increased significantly to date and are referred to as low-cost satellites (Boley and Byers, 2021). Starlink currently has around 4900 operational Starlink satellites in low earth orbit (LEO) and has approval for a total of 12,000 Starlink satellites (Wall, 2023).

At this point, it should be mentioned that SpaceX also offers other projects, such as “Falcon Heavy”, “Dragon” and “Starship”, in addition to the aforementioned "Falcon 9" and "Starlink" projects. During this case, however, reference is made to SpaceX's space debris avoidance strategies within the "Falcon 9" and "Starlink" projects.

5.2 Space Debris

5.2.1 Space debris: Understanding the crisis

Space debris started occurring after the first space mission SPUTNIK and increased further in the last 50 years. These defunct space objects can be divided in different sizes and therefore some are more critical for space missions, while smaller once are less. The main reasons for the creation of space debris are engine and battery explosions, as well as accidental collisions of man-made space objects (Bonnal and McKnight, 2016). An ESA study shows that there are 128 million objects between 1 mm and 1 cm, nearly 1 million pieces between 1 cm and 10 cm and 34.000 larger than 10 cm in space (Buchs and Florin, 2021).

Currently around 2600 operational satellites are stationed in the LEO orbit, which extends from the Earth's atmosphere up to an altitude of 2000 km. 22,000 objects are cataloged by the US Space Surveillance Network of which 84% are in LEO or crossing LEO. Since the number of space debris is increasing steadily, the probability of collisions rises as well and the secondary debris collides, with the consequence of even more newly generated space debris. This chain reaction is known as the Kessler Syndrome, named after its discoverer Donald J. Kessler (Buchs and Florin, 2021).

The future behavior of space debris is unstable and according to several studies, the space debris population would remain constant or even increase over the next 200 years even after new space activities are stopped, as new collisions would always take place and generate new space debris.

As the reality is rather the opposite, the situation is undoubtedly getting worse (Liou and Johnson, 2006).

5.2.2 Space debris: Risks for space missions

Since space objects in LEO have velocities between 7-8 km/s, compared to GEO at 3km/s, impacts from space debris and other space objects can have a much more significant impact on the mission. The damage of a collusion between spacecrafts and space debris can vary in terms of impact intensity. Low-intensity collusions can cause the disablement of subparts like solar panels and sensors, high-intensity collisions instead can have a much greater impact on the maneuverability of a spacecraft or in the worst case a complete loss of the space system itself (McKnight, Maher and Nagl, 1995). As Daniel Oltrogge and Salvatore Alfano are saying in (Oltrogge and Alfano, 2019), the estimated annual collision rate for collusions between active-on-active spacecrafts is at altitudes between 450 km and 500 km the greatest, with a significant peak at an altitude of 500 km. Collisions between inactive spacecrafts mostly take place in heights between 700 km and 900 km, with an altitude peak at 775 km. In this context both authors draw attention on the fact, that the above-mentioned numbers represent only catalogued space objects, which only stands for about 4% of the actual collision risk.

Setting now the connection between collision risk and mega constellations, which consist of thousands small satellites with a dry mass of a few hundred kilos in LEO altitudes, J. Radtke says in (Radtke, Kebschull and Stoll, 2017), that there is a calculated probability of nearly 70% a collusion with debris > 3cm will occur during mission life, with the result of a catastrophic collision.

Following on from this, J. Radtke refers to the fact that most small satellites in a mega-constellation are destroyed during their ascent through densely populated LEO to their destination. However, if a disposal rate of 90% of the small disused satellites out of a mega constellation is adhered, the collision risk is still 22% after 10 years of operational life and 42% after 20 years of operation.

An addendum to this is that a mission risk through space debris is always associated with costs arising from a mission failure. These costs are presented in chapter 5.2.4.

5.2.3 Space debris: Risks for earth environment and humanity

Since the effects of space debris are not limited to the pollution of the various orbits, such as LEO and GEO, the impact on Earth environment and the risk for the population must be highlighted as well. Currently, around one to two cataloged objects fall to earth every week, including helium tanks, fuel tanks and parts of the engine combustion chambers (Alby, 2010).

When a rocket is launched, the boosters which accelerate the rocket, are blown off after fuel exhaustion and return to earth and splash in the so-called “spacecraft cemetery”, which is in the southern part of the pacific. This procedure is called a splash-down and in the case of an Ariane 5 rocket for example, two 38-ton steel boosters were blown off and fell into the Pacific Ocean, with some of them still containing fuel residues. As of 2019 over 263 parts of space debris splash down in that area and approximately 10% to 40% survive the re-entry in the atmosphere of which 75% are dumped in the ocean (Bonnal and McKnight, 2016). Since the number of space operations is increasing in the near future, ocean splash-downs will also increase due to that common procedure of mitigating and disposing space debris on earth (United Nations, 2010). As mentioned above, fuel residues in fuel tanks can survive re-entry with hazardous chemicals like hydrazine, which is a very commonly used chemical in rocket propellant and are of very high concern to European Chemicals Agency (ECHA) stated in (Agency, 2008).

The level of risk to marine life will increase in the future, as the disposal of the ISS is currently being discussed. At the end of its mission, around 2031, the ISS will be brought down by a controlled re-entry into the South Pacific. This procedure is done by thrusting maneuvers, according the International Space Station Transition Report in (Hunt, 2022) and should guarantee a safe re-entry into atmosphere. Since the ISS is around 420 tones heavy and large as a football field, scientists comment that further dumping of spacecrafts is not sustainable and it should not be expected that the marine environment works in the same way as before (Davis, 2022).

As briefly mentioned above, the space industry trend is changing in the direction that less space debris should remain in space and thus the number of re-entering space debris will increase. Underlying this trend is the fear that even more space debris will significantly hinder Earth communication, space exploration, and space missions Jonathan McDowell says in (Abbany, 2021).

In terms of the risk of people being injured by falling space debris, can this currently be considered low. However, as briefly mentioned above, on average a part of a rocket weighing 2000 kg falls back to earth through uncontrolled re-entry about once a week, but mostly will fall into the ocean (Hall, 2014). As there have been no fatalities from falling space debris to date and the probability of being hit by such debris is only 1 in 10,000 (Louis-Charles *et al.*, 2023), this scenario is only briefly touched in this case study and will therefore be concluded with this paragraph.

In conclusion, however, it should be mentioned that the risk of humans being hit by falling space debris will play a greater role in the future, as more and more decommissioned spacecrafts are disposed on earth to keep the orbits clean for future space missions.

5.2.4 Space debris: Current and future costs

This subchapter deals with the various direct and indirect monetary costs, as well as the future costs of space debris. The direct costs are the costs that arise directly and therefore include costs such as the launch, the satellite itself and operations on the satellite. Reinforcing the shielding of satellites, debris avoidance maneuvers and the resulting fuel consumption and entailing non-usability of the satellite are some direct costs which should be mentioned in this context (Schaub *et al.*, 2015).

The major direct costs related to space debris is losing an operational spacecraft through space debris collision. Losing a satellite, not only the asset of the satellite is lost, instead it can no longer send data to earth, which means that important services on earth cannot be provided anymore. Referring to (Programs, 2011) around about 5 to 10 % is the part of the mission costs that can be regarded as costs for shielding and avoidance maneuvers. A cost comparison analysis is presented in chapter 5.3.3.

Indirect costs of space debris result due the problem of debris itself, less that it is attributed to the costs of individual missions. In this case, aspects that are associated with indirect costs are space debris detection services or manpower for space debris analysis. The Space Situational Awareness (SSA) for example is a department of the US Air Force (USAF), which detects all observable objects in space. The USAF freely provides the analysis information to space operators, even though they are not obligated to do so. However, most countries are not willing to share information due to national security concerns (Jakhu, 2011). This means that the cost of space debris analysis is passed on to the American population, with investments between 2006 and 2015 amounting to around $5.3 billion, not including mission and maintenance costs (Schaub *et al.*, 2015).

The direct costs for space operators are currently low related to space debris, which is why they presently have little need to act on active response strategies. As the risk to space operators from space debris will increase significantly in the future due to an exponential increase of space activities and the potential consequences like unusability of certain orbits, more stringent methods to mitigate space debris on a voluntary or regulatory basis will be necessary, which will subsequently lead to a sharply rise in costs (Undsethi, Jollyi and Olivarii, 2020). The costs of future space debris cannot be estimated precisely. As McKnight says in (McKnight, 2010) that it will be less expensive to collect one large space object now (divers thousand kilograms) than several small fragments created by collisions. It is therefore more practical to remove large space debris fragments now than small space debris particles in the future. If this is implemented promptly, it is not necessary to collect small fragments, as the number of centimeter-sized fragments is more than 100,000, which would lead to unpresentable economic costs (Schaub *et al.*, 2015).

In addition to the cost of extra shielding and collision avoidance maneuvers, the cost of space debris removal should also be considered in this context. Apart from two space shuttle missions in 1984, in which the astronauts collected the space debris manually via space walks and then stored it in the space shuttle itself, there have been no other similar missions to date (Buchs, 2020). NASA has put the cost of this mission at around $450 million, with the actual space shuttle cost per flight believed to have been $1.6 billion (Wall, 2011).

In 2025, however, two missions are planned, ClearSpace-1 and CRD2, which aim to collect a 120 kg space bulkhead fragment. The cost of these missions will be around €120 million and ESA members have agreed to contribute financially to the first of these missions (Devlin, 2019).

The direct costs caused by space debris will increase significantly in future, due to active responses of space operators and an increase of indirect costs to space organizations by expanding resources for space observations for visible man-made space debris. Currently, the data on future costs of the consequences of space debris caused by human space missions is still very thin, which is why only estimates can be made (Buchs, 2020). However, it can be said that the increase in the number of space missions will also lead to an increase in space debris and the subsequent costs will multiply as a result.

5.2.5 Space debris: Collection and detection methods – a short overview

Active Debris Removal (ADR) is the term that includes various debris removal strategies to reduce the collision risk for operational spacecrafts in different orbits. As shortly mentioned in subchapter 5.2.4, the first space debris removal mission was carried out by the Space Shuttle in

1984 in which two satellites were collected manually by the astronauts, which made the mission very costly.

Nowadays, however, more innovative, and less expensive methods of removing world waste are being developed. Laser-based (LODR) is one of the techniques, which shoots laser plasma jets from earth ground on the objects to slow them down and causing them to burn-up in the atmosphere. This system is according to (Soulard *et al.*, 2014) very cost effective to remove large and small debris fragments from the orbit, even though the systems readiness and response is not satisfactory. The future purpose of the system will be placing it in space to scan, shoot and track small-scale hyper-velocity space debris, which is a solid approach to use that system effectively and efficiently, however, installing the system in space could be a challenge in the future and needs to be evaluated.

Another approach to deorbit space debris, are solar sails. Solar sails use immense surface as means of transportation and can help to reduce the deorbiting time, compared to only use the surface of the spacecraft itself. Since sails are in general a beneficial way to use, but negative effects of using it can clearly predominate here, as a lift of the spacecraft can be generated and the opposite of reducing deorbiting time could be the case, according to Romagnoli and Theil in (Romagnoli and Theil, 2012).

The last method of space debris removal is called the harpoon target capture method. Here, a harpoon is fired onto a space debris fragment by a so-called "chaser" and pierces the component in such a way that it can then be pulled down to the upper layer of the atmosphere. The fragments can then be burned-up by a controlled re-entry. This process can be used for component sizes of up to over a ton, whereby the shell thickness of tanks with up to 3 mm can also be penetrated here. According to (Dudziak, Tuttle and Barraclough, 2015) this process can contribute to space debris removal, but still needs to be sufficiently researched to ensure its effectiveness. In conclusion to this subchapter, however, all above-mentioned methods for space debris disposal are in the experimental or conceptual phase and further research is required in this regard (Mark and Kamath, 2019).

5.2.6 Space debris: International instruments

The first international space rights, which were established to reduce space debris, were created by NASA in 1995 as the first space agency. Following on from this, in 2001 the US government drew up regulations relating to the problem of space debris. The so-called Orbital Debris

Mitigation Standard Practices (ODMSP). The ODMSP contains regulations that are intended to limit the creation of new space debris, as well as the containment of long-lived space debris. The principles of the guidelines are based on four main objectives, which are to limit the generation of mission-related space debris, to limit the generation of space debris through accidental explosions and accidental collisions, and to remove structures at the end of their operational life. With an update in 2019, the guidelines remained largely the same, but a few changes were made in relation to each objective (Liou *et al.*, 2020).

On an international basis the Inter-Agency Space Debris Coordination Committee (IADC) guidelines include the impact of space debris on the environment through space missions, focusing on the two most used orbits, LEO and GEO. These guidelines were established in 2002 with a revision in 2007 and has space agency members from 10 countries including the European Space Agency (ESA). The four main principles of IADC guidelines are identical to the ODMSP guidelines with: Limitation of debris released during normal operations, minimization of the potential for on-orbit break-ups, post-mission disposal and prevention of on-orbit collisions. The guidelines further recommend to create space debris mitigation plan of each space mission and to limit orbital life time of space crafts, after mission end, to be 25 years (IADC, 2007).

The two guidelines mentioned above show that various countries are addressing the problem of space debris and are prepared to act at a global level. In this context, however, the limitation of these guidelines should be addressed here as well, since those are not an international treaty to tackle the problem of space debris, much more they are merely guidelines, which means that these rely mainly on voluntary basis and are not binding for space activities (Yang, 2023).

5.2.7 Space debris: Future response strategies and incentives for the space industry

As discussed in subchapter 5.2.6 the current international laws are on a non-binding basis and only focus on the issue of newly created space debris. Once a space object or space craft is launched into orbit, space agencies and space operators currently have only little incentive to reduce the risk of space debris. This subchapter will therefore look at future response strategies and incentives for space operators to address the issue of space debris.

When looking at regulatory measures, a distinction can be made between a binding international set of rules, marketable permits, and regulatory fees.

Binding international set of rules

According to (Buchs and Florin, 2021) new binding multilateral agreements between spacefaring nations in this context would prevent the efforts of some to avoid space debris from being exploited by others. However, such an agreement will not be reached soon, as the goals and agendas between the space nations differ. To this end, large space nations could set a good example and promote unilateral measures to prevent space debris, as smaller nations are often guided by the regulations of large countries.

Marketable permits

Marketable permits can be seen as permits or licenses issued by the government for a defined action. Such marketable permits were currently used in the environmental and energy sector for pollution management to control Greenhouse Gas (GHG) emissions and ratio the use of CPRs (Tietenberg, 2006). Two main objectives need to be mentioned in this context, the cap-and-trade in which the regulator sets an absolute budget (e.g. total quantity of fish catches permitted) and the credit trading system, in which the regulator restricts the relative quantity of an activity (e.g. no net rise in emissions) (Buchs, 2020).

Due to various costs, such as costs lowering the quantity of space debris created during space missions or the loss of space objects during space missions, marketable permits can be considered according to (Buchs, 2020) as more efficient compared to command-and-control regulatory, due to the fact that the costs for remediating space debris will evolve with innovations and not all actors are able to utilize this very, resulting in an inequality in compliance costs for all actors.

Regulatory fees

Regulatory fees and market permits have a similar approach. A regulatory fee is independent of the quantity of activities carried out; rather, the regulatory fees set an upper limit for the avoidance costs, but without warrant for the extent to which an activity is carried out (Wiener, 1999). If one imposes regulatory fees on the problem with space debris, it is difficult to calculate the correct amount of the fees, because the regulators usually lack information on current and future abatement costs. If, for example, services for the removal of decommissioned satellites are offered in the future, the costs for this are still difficult to estimate today. In this context, one should be aware of two questions: Should the fee be paid before the start of the mission based on the risk of space debris generation? Or should the fee be based on the amount of space debris actually generated during the mission? (Buchs and Florin, 2021) According to the Federal Communications Commission (FCC) report from 2020 in (FCC, 2020) a possible performance bond for successful post mission disposal may be a way to provide monetary incentives to space operators after mission life. Beforehand, the space operators would have to present their space debris mitigation plan to the relevant authority, and have it approved. This approach would work according to a deposit principle, which means that space operators have strong monetary incentives to remove space objects from orbit at the end of their mission life to get their deposit back.

Financing programs – bounty payments as incentive

Sharing the costs of space debris removal evenly between spacefaring nations is a challenge and is presented in this sub-chapter, in part together with insurance incentives.

A possibility to tackle the issue of space debris could be some sort of managing funds through bounty payments, which are financial incentives to regulated commercial entities that conduct remediation actions. For this scenario, costs would have to be scalable, i.e. the cost of removing a satellite compared to the cost of removing a rocket body, which usually weighs over a ton. If one continues this idea according to J. Carroll in (Carroll, 2019), there may be future actions with bounty hunters and a completely new branch of business in the space industry. According to J. Carroll, new laws and regulations would have to be established to structure this model, and he goes on to describe this method as the most efficient for saving costs in relation to space debris mitigation.

Insurance Incentives

There are two types of insurance for satellites, first-party (property) and third-party liability (TBL), whereby the first only insures the loss of the satellite and the second insures the damage caused by the satellite to third parties. The insured entity can use both types for the launch, the in-orbit missions or for both at the same time, with first party insurance being the most used (Buchs and Florin, 2021).

In this context, insurance can work as a lever to reduce the space debris population in space. Insurance companies could grant discounts for compliance with space debris mitigation guidelines or, conversely, demand higher prices if the submitted space debris mitigation plan is inadequate (Harrington, 2015). However, since regulations on space debris are currently insufficient, insurance companies cannot orient themselves to them and adapt other possible contractual clauses. In addition, due to the remoteness of space, liability issues are still difficult (Buchs and Florin, 2021).

Corporate social responsibility

Space operators' reputation and brand identity can promote a sustainable use of space. If customers of satellite-based services are shown transparently what the space operators or agencies are doing in terms of sustainability in orbit and on earth, offer a competitive advantage and greater prestige. This type of information is, however, currently not available, which is why the World Economic Forum Global Future Council on Space Technologies wants to change this and introduce a so-called Space Sustainability Rating (SSR). This could be an approach to incentives the industry to develop their missions according to sustainable und responsible actions. The SSR includes factors like, on-orbit fragmentation risk, collision avoidance capabilities, detectability of space debris, data sharing and adoption of international standards. If a space operator signs the SSR evaluation, the assessment of sustainability will take place over the entire mission, from the design phase to disposal. A rating would then be valid for a certain period of time after which it would be re-evaluated (Rathnasabapathy *et al.*, 2020).

As such ratings are already very popular in other industries (Cordero, Melgar and Márquez, 2019), the SSR could be a tool to incentivize space operators to act in a sustainable and environmentally friendly way along with an increased transparency (Buchs and Florin, 2021).

5.3 SpaceX's role regarding space debris

This chapter will present SpaceX's strategies in relation to space debris avoidance. It will start by outlining SpaceX's general strategies, with the following sub-chapters making direct reference to two of SpaceX's missions, the Starlink mega-constellation and the Falcon 9 rocket's reusable boosters.

5.3.1 SpaceX's overall strategies to tackle the issue of space debris

In the following, general strategies of SpaceX are presented, which contribute to the containment and avoidance of space debris. These strategies comprise: SpaceX's rapid deorbiting, transparent data sharing of space debris, satellite resilience and state of the art space debris collision avoidance systems.

Fast deorbiting

Fast deorbiting means that a space object is removed from orbit as quickly as possible at the end of the operational life. SpaceX is a pioneer in this respect, as they remove its satellites from orbit no later than 5 years after the end of their mission (Boley and Byers, 2021). The current guidelines recommend disposing of the space object from LEO no later than 25 years after the end of the operational life (Buchs and Florin, 2021). Not only satellites that have reached their operational lifetime are deorbited promptly by SpaceX, but also satellites that show issues during their ascent or operational life with a possible consequence of unmaneuverability, are removed directly from orbit to prevent debris generation. Updates from SpaceX show that their satellites are now deorbited to earth within weeks after their operational life, whereby care is taken to ensure that there is always enough propellant to deorbit the satellites within 4 weeks from the respective orbit (SpaceX, 2022).

According to (Zhang *et al.*, 2022) a rapid removal of non-functioning or decommissioned satellites from frequently used orbits, such as LEO, is necessary to avoid far-reaching consequences due to collisions with the result of newly created debris.

Transparent data sharing

Another strategy SpaceX is pursuing to address the problem of space debris is the transparent sharing of data related to collision risks and detected space debris. The aim here is to set a good example and encourage other space operators to share their data with the public to avoid the risk of collisions with the result of newly created space debris. SpaceX wants to promote further disclosure of data and contribute as a first mover to encourage other space operators and space agencies to do the same. Currently, SpaceX has also submitted data on its satellite fleets, such as the status and number of maneuvers caused by the risk of collisions with other space objects, to the Federal Communications Commissions (FCC). No other operator has ever disclosed this data in the past. This demonstrates the importance SpaceX places on the sustainable utilization of the common good space (SpaceX, 2022). Comprehensive disclosure of SpaceX's data can increase the accuracy of calculations and mitigate conjunction events. Increased data sharing can also help to avoid unnecessary positioning maneuvers, as more accurate information about the positions of other space objects will be available (Cooper, 2017).

In conclusion, according to Dr. Nathaniel Dailey in (Dailey, Toner and Murphy, 2022), the U.S. sees the lack of informative space communications as a driver for misinterpretation and miscommunication, which in turn can affect the safety of space operations.

Satellite resilience

On the report of SpaceX (SpaceX, 2022) is the reliability of their satellite networks at present over 99% with in a number of 2000 satellites, 1% failure rate after being launched to orbit.

SpaceX employs several methods to protect its satellites from flying space debris and to minimize the results of such impacts with the result of newly created space debris. Design adjustments of the satellites to protect sensitive components such as the battery, which could explode if hit by space debris, and satellite chassis with a narrow profile are just two aspects that lead to less space debris generation. Speaking of satellite design "simplicity" is one of the key factors SpaceX is pursuing. According to an interview of Elon Musk in 2012 (Chaikin, 2012), the success of SpaceX is mainly due to the simplicity of its space objects, which can be seen as a driver for reliability and lead to cost reductions. Further Musk said:

> "Think of cars, is a Ferrari more reliable than a Toyota Corolla or a Honda Civic?"

Thanks to the design of SpaceX satellites, which increases the launch tempo and reduces costs at the same time (Linville, Capt Dax and Bettinger, 2020), the probability of residue-free burn-up of satellites via re-entry into the atmosphere is significantly higher with less prevalent risk to people or the environment on earth (Jones, 2023).

Operating in low orbits

Another strategy used by SpaceX to reduce the risk of space debris is operating in low orbital altitudes below 600 km. The great advantage of this low altitude is that satellites, which have become inoperable or no longer maneuverable, are pulled to earth by the gravitational pull within 5 to 6 years and demise in the atmosphere. This natural method of deorbiting contributes significantly to the rapid removal of satellites in constellations from highly frequented orbits. Other space operators, for example, use altitudes of 1000 km, for which a deorbiting time of several hundred years is predicted if manual deorbiting is no longer possible (SpaceX, 2022). The results of Hugh Lewis in (Lewis, 2020) show that lowering only 20% of the satellites in a constellation from altitudes at 1100 km to 550 km can reduce the overall impact of constellation sustainability, whereas the need for a high post mission success rate is obsolete. Furthermore, this results in the advantage of high disposal reliability after the end of the mission, which supports SpaceX's assumptions. In conclusion, however, the author adds that the increased collision activity below 550 km due to failed space objects is a compromise resulting from the improvement in sustainability.

In addition, according to (Shao, Koltz and Wertz, 2014) operational missions at low altitudes are also associated with lower risks and costs in terms of mission success. The short operational periods, simple design and the available replacement of small satellites play a major role here. Lower risks also means a lower chance of failure due to space debris.

Finally, according to (Wertz *et al.*, 2020) a further reduction in altitude to below 500 km of satellites is even more positive in terms of space debris, as satellites are deorbited within days or months after operational life due to mentioned natural drag to earth plus the space debris density is much less than at traditional satellite altitudes.

5.3.2 SpaceX's strategies for mitigation based on Starlink and Falcon 9

In the previous subchapter 5.3.1, SpaceX's general efforts to avoid space debris were presented. This subchapter shows SpaceX's strategies based on Falcon 9 and Starlink missions to mitigate space debris. Chapter 5.1.1 presented both missions and gave an overview, which is why only a brief introduction to the missions will be given here and the focus will mainly be on the strategies SpaceX pursues to mitigate space debris.

The reusability of launch vehicles is an important cornerstone for the development of a fully sustainable space industry. Not only the financial factor, where the cost of reusing rocket bodies can be reduced by 20%, but also the "green" approach to the development of rockets that can be repaired, recycled, reused, and thus have a long life (Richardson and Hardy, 2018).

Falcon 9 – Overview

The Falcon 9 is the first orbital class rocket with a first stage reusable boosters and is designed to transport people and payload into space. Thanks to the reusability of the boosters, Falcon 9 can be used several times, while reducing the costs of launches for SpaceX compared to other space operators. Since the environmentally impact of rockets can be immense, the reusability of space crafts is a necessary tool to mitigate space debris in space and on earth (Drolia and Babu, 2022).

The Falcon 9 is a 70-meter long rocket with two stages, stage 1 and stage 2, of which stage 1, about two-thirds of the entire rocket height, returns to earth accurately and is refurbished for reuse (Sippel, Stappert and Koch, 2019). This return method is called vertical takeoff, vertical landing (VTVL) and is based on stage 1 being decelerated by several maneuvers after separation from stage 2 and shortly before touchdown on earth slowed down by an engine ignition to perform the touchdown on a passive landing barge (Stappert *et al.*, 2019).

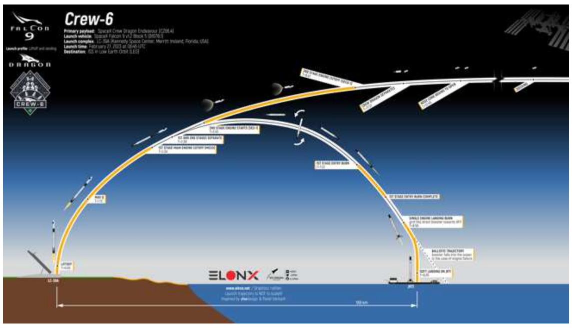

Figure 1 SpaceX Falcon 9 Launch Profile (Elonx, 2023)

Figure 1 shows the re-entry process of the Falcon 9 rocket. As seen, the first stage will be separated from the second one after a specific time and returns to earth for landing on a barge in the ocean.

Falcon 9 – Rocket bodies in LEO, risk from uncontrolled re-entry and impact on debris population

To understand what positive impact, the reusability of rocket boosters has on the space debris population and on earth, the following compares how many disused rocket boosters/bodies are currently in different orbits and how often some end up on earth via deorbiting.

As mentioned at the beginning of this study, around 355 pieces of space debris fall back to earth every year and in the period from 2008 to 2017, around 40 rocket bodies re-entered the earth's atmosphere in an uncontrolled manner (Pardini and Anselmo, 2019). It should be added that more than half of all re-entries are uncontrolled, and considering the entire period of human spaceflight history, every 5th rocket body has come back to earth by uncontrolled entry. If it is assumed that up to 40% of the mass remains after re-entry, it was calculated according to Carmen Pardini in (Pardini and Anselmo, 2018) that approximately 1650-2200 metric tons (1 metric ton = 1000 tones) of rocket bodies impacted uncontrolled on the earth's surface. Further, Carmen Pardini said, that the risk of people getting injured through uncontrolled rocket body re-entries will increase in the next years due to the fact of a rise in space activities and a growing population density on earth. But detailed and reliable data of future casualty's expectancies are not available for public and therefore difficult to obtain. Since some of the rocket boosters return to earth immediately after blasting off. Through earth drag, they will crash on land or in the oceans, which was discussed in chapter 5.2.3. Returning and reusing boosters can help to significantly reduce the negative impact on the earth's environment, since rocket bodies also detect toxic, environmentally harmful residues of propellant, such as hydrazine.

According to Virendra Kumar Verma in (Verma, Gangadhari and Pandey, 2023) SpaceX is setting an example with its Falcon 9 reusable first stage, as it is a great opportunity to significantly reduce the increase of new rocket bodies or in general space debris population in LEO.

Starlink – Overview

In this subchapter, SpaceX's strategies regarding space debris avoidance are presented using the Starlink mega-constellation.

As shown in chapter 5.1.1 the Starlink mission is a mega-constellation, which provides broad band internet, with currently 4900 small satellites in LEO with the target of adding another 12.000 until 2027 and the approval for 30.000 in total with the FCC (Boley and Byers, 2021). The Starlink satellites are used as individual mirrors, which reflect signals between terminals and ground stations to adopt optical inter-satellite links to build the mega constellation in LEO (Li *et al.*, 2023).

Starlink – Strategy

SpaceX produces their mega constellation satellites in mass productions operating in LEO. Each Starlink satellite has a lifetime of around 5-6 years until they get deorbited into earth atmosphere. Each Starlink satellite is equipped with its own space debris collision system, with the use of on ground space debris threatened data automatic avoidance maneuvers are initiated for each individual satellite (Boley and Byers, 2021), (Hongqiang and Zhanyue, 2020). These collision avoidance maneuvers are then initiated via thrusters on the satellite itself and lead to an increase or decrease, change of speed or adjustments of inclination angles of the satellites. Conventional collision avoidance maneuvers are performed manually using information from the space situational awareness SSA, which were used to time avoidance maneuvers in the upcoming days and weeks. However, this cannot be applied to mega constellations, as these comprise an enormous number of satellites for which Starlink uses the mentioned self-driving system avoidance system with estimating its individual runtime via GPS and communicates it with the on earth stations to schedule their collision avoidance maneuvers (Li *et al.*, 2023). According to (Ren *et al.*, 2021) can the calculated collision risk for Starlink satellites be decreased by 60% during the operational life in orbit due to the fact of using collision avoidance systems.

In the initial phase of the Starlink satellites, some components in the Starlink satellites survived re-entry, but this was changed by adjusting materials, resulting in an almost complete burn-up of the satellites (Boley and Byers, 2021). According to (Ren *et al.*, 2021) 95% demise rate on re-entry is the current percentage value of Starlink satellites, while 10 – 40% burn-up rate is common percentage value of other space objects.

Another strategy that SpaceX is pursuing in relation to Starlink is the use of low orbital altitudes. With operational altitudes of 340 km and 550 km, the Starlink satellites are gradually pulled towards the atmosphere by the earth's gravitational pull even in the event of a propulsion failure and are naturally deorbited, which in turn accelerates the deorbiting time and reduces the risk of collisions with the result of newly created debris (Zhang *et al.*, 2022).

5.3.3 Cost comparison between SpaceX and other launchers in terms of reusable Falcon 9 and Starlink overall costs

In the previous subchapters, the strategies of SpaceX in relation to its Falcon 9 and Starlink missions were outlined. This section presents the resulting cost advantages that SpaceX achieves as a result.

Falcon 9 – Cost advantageous resulting from reusability

The reuse of rocket stages not only reduces the problem of space debris and the negative impact on the earth's and space environment, but also makes a significant contribution to reducing costs for the space operators.

As already presented in subchapter 5.3.2 SpaceX reuses the first stage for its Falcon 9 rocket by returning vertically to earth and land. The cost of manufacturing a SpaceX first stage is approximately 75% of the cost of manufacturing a complete Falcon 9 rocket, so a major part. In addition to reusability, SpaceX relies on complete in-house production from the planning phase including design, engineering, manufacturing, software, integration, testing, launch, and operations through to final manufacture (Jones, 2018).

According to (Elonx, 2020), Elon Musk said in the interview with Irene Klotz (Senior Space Editor Aviation Week) in Aviation Week (Klotz, 2020), that SpaceX offers a launch of a reused Falcon 9 for $50 million with only marginal costs of $15 million, with $10 million the major amount of manufacturing a new second stage, which is not reusable. The remaining $5 million includes the refurbishment of the fairing, the helium, the fuel, the oxygen, and the cost of the recovery. The R&D costs for the reusable Falcon 9 were estimated at around $1 billion, and if this is now applied to the 213 reused launches (SpaceX, 2023), an additional $4.7 million is added per launch. Which makes this approach always profitable and increases the profit margin with each reusable launch. If SpaceX now launches its own satellites into orbit with the Falcon 9 rocket, they only pay the $15 million as marginal costs per launch for the Falcon 9 reuse.

Since data regarding the costs of Falcon 9 launches is quite thin, below further sources regarding costs are listed. A one-time use of the Falcon 9 launch has a launching price of $61.2 million and launch costs of $36.7 million (as of 2016 and assumed gross margin of 40%), bringing the launch price of the first stage to $46.5 million (75% of launching costs) and launch costs of $27.5 million for the first stage. With a service life of 15 flights in operation for a first stage Falcon 9 booster, it is expected to reduce launch prices by $13.7 million to $48.3 million and increase gross margins to 77% (Richardson and Hardy, 2018), (De Selding, 2016).

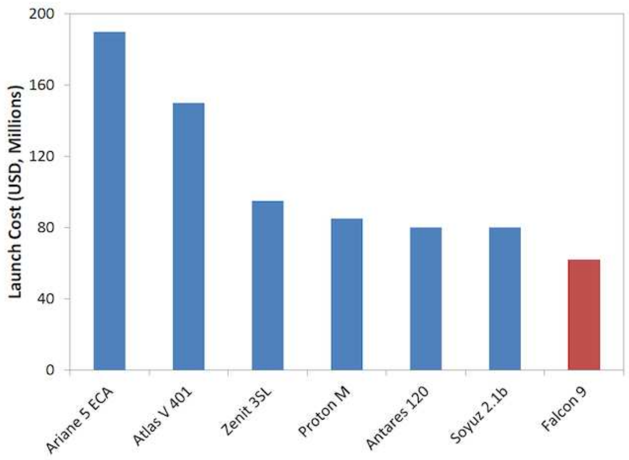

Figure 2 Comparison launch cost, source: (Richardson and Smart, 2017)

As seen in Figure 2 even without the further cost savings due to the reusability of the boosters, the Falcon 9 is the cheapest launch system compared to the competition. If reuse is always pursued further, the negative impact through disused rocket bodies on environment and the generation of space debris can be significantly reduced in addition to the cost savings.

Starlink – costs advantages in comparison to Amazon Kuiper and OneWeb

By using its own reusable Falcon 9 launch vehicle, SpaceX can offer the launch costs of a single Starlink satellite at a significantly lower price than its competitors OneWeb and Kuiper. The other two competitors Kuiper and OneWeb are as well delivering wireless broadband internet. The launch costs for a Starlink satellite with a mass of 260 kg are just $0.5 million, whereas the launch costs for a Kuiper satellite are three times as high, namely $1.5 million and for OneWeb with \$2 million four times higher. The comparison of the estimated net present value (NPV) of the three competitors in the period from 2020 to 2025 is shown by Osoro and Oughtin in (Osoro and Oughton, 2021) in which Starlink has the lowest NPV at \$0.6 million per satellite, OneWeb \$5.6 million and Kuiper \$3 million. Further Osoro and Oughtin say, that Starlink offers the lowest cost range per subscriber density of 0.005 – 1.0 km^2 with \$10 – \$100 and Kuiper with \$30 – \$400.

Mega constellations can be seen as the trend for the next few years, as their simple design, low manufacturing costs and fast construction time make them well suited for mass production (Allen, Wickham-Eade and Trichas, 2020). This means that replacement satellites can also be put into orbit at low cost. These can then replace satellites that have failed, which makes a new rocket launch not necessary. The inactive satellite is then deorbited and demises in the atmosphere (Boley and Byers, 2021).

5.3.4 Starlink's impact on space debris population and future threads through mega constellations

Since mega constellations like Starlink are composed of a large number, currently nearly 5000, of small and simple satellites, the traffic density in LEO is increasing further also due to competitors like OneWeb. Therefore, the risks of such mega constellations on the debris population, the risks for the constellation itself and the risks for other space missions in LEO is presented in this following subchapter.

According to Aaron C. Boley and Michael Byers in (Boley and Byers, 2021) is the current trackable number of space debris larger than 10 cm in LEO at around 12,000, which represents the same amount of Starlink satellites after mission completion in the first phase. These 12,000 satellites will then have a total mass of 3,000 tons and will be replaced by new Starlink satellites every 5-6 years at the end of their operational life. Since the deorbiting of the satellites will cross high traffic areas, collision risks will increase since the deorbiting time takes roughly 6 months (SpaceX specifies 4 weeks), therefore around 10% of the satellites will always be in the phase of deorbiting. The risk during the ascent and the descent, was discussed in (Radtke, Kebschull and Stoll, 2017). The author calculated that crossing the dense LEO orbit of mega constellations has an almost 70 percent risk of collisions with space debris larger than 3 cm.

The study (Ruan *et al.*, 2023) was able to show through a simulation that phase 1 of the Starlink constellation has a collision risk of at least one crash with space debris of 70% over its lifetime.

The authors put the general short-term risk of a collision between Starlink satellites and space debris at between 30% and 40% after deployment of the satellites. According to Carmen Pardini and Luciano Anselmo in (Pardini and Anselmo, 2020) an increase of just 1000 satellites with a mass of 250 kg (similar to Starlink) added in altitudes between 300 km and 1000 km can rise the collision rate by approximately 30% with space debris larger than 10 cm. The authors go on to say that an increase in the probability of mega constellations collision and space debris over the next 25 years could rise to up to 50%. However, to use and expand mega constellations sustainably in the future, a disposal success probability of 95% or even 99% is a definite need.

However, the collision avoidance system of the Starlink satellites can also lead to an increased risk of collisions. Due to unnecessary maneuvers performed by Starlink, the authors in (Li *et al.*, 2023) were able to determine an increase in the risk of collisions. In this specific case, the altitude of one Starlink satellite was changed to avoid a collision with a third-party satellite. Due to the uncertainty of time-varying and a resulting inaccuracy of the satellite locations, an almost near-collision with another second Starlink satellite was caused, although the probability of a collision with the third-party satellite was well below the required minimum probability.

These maneuvers cost fuel, reduce the operational life and increases the risk of collisions with the own network in certain situations.

6 Teaching note

6.1 Synopsis

SpaceX is a growing private space company founded in 2002 by Elon Musk, who is known as the owner of Tesla and co-founder of the payment service provider PayPal. The space debris crisis is a current but even more pressing issue for humanity, the Earth's environment, the space environment, and space missions in the future. Space debris are fragments that represent small to large man-made remnants of space missions that were created by collisions between space objects and orbit the earth at different altitudes. SpaceX is playing a leading role by demonstrating through their adaptive strategies how to mitigate this crisis and potentially incentivize competitors to adopt these mitigation strategies. These strategies include, among others, the reuse of rocket boosters and the rapid and controlled deorbiting of satellites with 95 percent burn-up in the atmosphere, which significantly reduces the generation of new space debris, prevents risk for earth and saves costs at the same time.

With the space debris crisis becoming more and more apparent, governments and space authorities will be forced to introduce ever stricter requirements regarding space debris prevention in the future, and space companies should be prepared for this at an early stage to stay competitive in the market and should be able to adapt their business strategies to these new business requirements.

6.2 Target audience

This case study is tailored for bachelor and master students in fields of Management, Finance and Environmental Science, since diverse aspects from Strategic Management to Technological Innovation and Environmental Sustainability are covered in this study.

6.3 Teaching Objectives

The teaching objectives of this study is to give students an overview of the strategies that companies can use to manage global crises to mitigate potential damaging consequences for their business. In this case, students can use the four theoretical frameworks presented to bridge the theoretical information from the case study chapter 5 including the business adaptive strategies from SpaceX to deal with the space debris crisis. This will help to better understand the different strategies of space companies in relation to space debris in order to address this increasingly evident crisis.

The teaching questions lead the students to a comprehensive understanding of the case to gain a holistic view and connect the four theoretical frameworks dynamic capabilities, adaptability, and agility, eco innovation and CSR reporting to real world crises.

6.4 Teaching Questions

This subchapter lists the teaching questions which will be handed out to the instructor of the case study, which should provide guideline for the procedure of the overall mode of operation.

1. **How can transparent CSR reporting by SpaceX help to showcase their efforts in terms of space debris avoidance to increase stakeholder confidence and credibility in the space industry?**
2. **Using the VRIO framework, to present SpaceX's sustainability technologies as a strategic asset. How does these assets help to mitigate the space debris crisis?**
3. **Analyzing how SpaceX's dynamic capabilities, including reputation management, adaptability, and agility, enable the company to remain at the forefront of space debris combat.**
4. **Reviewing the specific eco-innovative capabilities SpaceX has demonstrated in its quest to reduce space debris. How can these capabilities influence industry standards and contribute to a more sustainable approach to space exploration?**

6.5 Analysis and discussion

The first question which will be discussed here is regarding a transparent Corporate Social Responsibility (CSR) reporting as tool to showcase SpaceX’s efforts regarding the space debris crisis.

1. **How can transparent CSR reporting by SpaceX help to showcase their efforts in terms of space debris avoidance to increase stakeholder confidence and credibility in the space industry?**

The aim of this question is to analyze CSR reporting as communication tool for environmental crises like space debris. As described in chapter 4.4, a transparent CSR reporting provides information on economic, environmental, and social performances of a company to their stakeholders to provide transparency and to ensure a sustainable development of the company. CSR reporting includes stakeholder like investors, regulators, and the public.

Companies aim to be an attractive investment for investors, and CSR reporting is one aspect that can convince investors to invest in companies with a transparent CSR reporting. Enigmatic to this is, that companies which practice CSR reporting can improve their financial reporting quality (Wang, Cao and Ye, 2018) which leads to a better understanding of a company’s credibility for potential future investments. In addition, investors may be more interested in companies with transparent CSR reporting, as these companies will presumably have to overcome fewer barriers due to environmental regulations in the future to stay competitive in the market and thus potentially achieve higher value in the future. In the case of SpaceX, the technological efforts they undertake to save the earth and space environment from newly created space debris could bring attraction to investors as they are interested in further space missions of SpaceX and to achieve a higher order book and consequently higher revenues.

Regulators, such as governments, for example, will be forced to impose legal principles on space companies in the future regarding mitigation of space debris, whereby the strategies in CSR reports from SpaceX can be a guidance for just this and thus legally appropriate principles can be created. Further on this, SpaceX can avoid financial consequences due to non-compliance to regulatory frameworks as they already use transparent CSR reporting, which increases the collaboration with regulators and shows the importance of SpaceX’s space debris mitigation strategies such as reusable boosters or a fast deorbiting of Starlink satellites after their operational life.

As SpaceX is currently the only space company using space debris mitigation strategies like Falcon 9 reusable boosters or Starlink’s demising materials for mega constellation satellites, while also reducing costs at the same time, a transparent CSR reporting could also be an incentive for other space operators to adapt SpaceX’s strategies with the goal of compliance with future legal frameworks, attenuate the space debris population with its negative consequences and save costs at the same time.

Finally, CSR reporting as communication tool. As SpaceX already attaches great importance to open communication in relation to space debris identification plus makes the information openly available as described in the case study chapter, transparent CSR reporting can serve as an additional communication channel for SpaceX's strategies in relation to space debris detection.

Through such open communication, collaborations between space operators and space agencies can be enhanced plus a monitoring and reporting forces can be bundled. These efforts can then be used to achieve a collective generation of knowledge and a clear willingness to tackle the space debris crisis. As shown in the case study, SpaceX had cited the lack of communication between space companies as a reason that collision avoidance maneuvers often must be initiated based on ignorance.

2. **Using the VRIO framework, to present SpaceX's sustainability technologies as a strategic asset. How does these assets help to mitigate the space debris crisis?**

The second question deals with the VRIO framework, which was developed by Jay Barney in 1991 and represents a framework of analyzing a company’s capabilities to gain and sustain competitive advantage.

Value stands for the capability SpaceX’s assets create to gain competitive advantage. One of the main values SpaceX has, is their R&D in the reusability of space objects. This value creates an immense cost advantage against the competition and contributes markedly to mitigate the space debris population in LEO plus saves the earth and space environment. With the reusability of the Falcon 9 stage one, SpaceX is able to launch space objects at low-cost while being the only space company currently addressing the space debris crisis incorporating this technology, contributing to cost-effective and sustainable space exploration. This cost-effectiveness has made space missions more accessible to a wider range of customers, enabling more R&D concerning the population of space debris. Since a booster has already being launched once, the probability of a successful second launch is high. This not only boosts SpaceX's credibility rather it enhances its reputational value generating competitive advantage. Since the space debris mitigation strategies were determined based on Falcon 9 and Starlink, the value of Starlink should be mentioned here as well. The modular and simple design saves costs plus enhances the production speed, the use of materials that burn up almost completely on re-entry (95%) protect the earth environment. Furthermore, the smooth replacement of defunct satellites is among the various abilities of Starlink that add significant value to the company and diverse environments.

Rare are SpaceX’s R&D resources in reusability of space objects in the space industry, while currently being the only space company successfully relaunched several hundred first stages.

Other private space companies like Blue Origin are still struggling with their technology and haven’t launched a single reusable rocket to date. With SpaceX actively investing in R&D concerning the sustainable utilization of space, the company sets standards in the industry for future operations plus does not have to adapt its missions to upcoming requirements of regulatory bodies resulting in a rare resource. In addition, SpaceX is able to launch its own Starlink satellites into orbit at marginal costs, as it only has to bear the actual production or processing costs of Falcon 9 and does not have to rely on the rockets of its competitors, which in turn makes it a rare resource, as no other private space operators is currently possess this capability.

More, SpaceX benefits from first mover advantage in the market, since contracts with customers like the NASA and reputation due to successful space operations is already build up, thus hard to set up competitiveness for later entrants since the market is dominated by one player and one could almost speak of a monopoly SpaceX is having here.

Imitability represents the barrier which the competition must overcome to replace or copy SpaceX’s products and services. Since the capabilities of SpaceX are difficult to imitate, the company enjoys a dominant market position in the private space sector. The imitation of SpaceX technology of reusable Falcon 9 boosters and its capabilities to send their Starlink satellites in space at low cost represent a high barrier for the competition like Amazon or OneWeb. The technology to refurbish the boosters of Falcon 9 for a second launch requires technical knowhow, which SpaceX developed internally and no other space company accomplished something corresponding to date.

Organizing value with the robust support of youthful staff. Employees between 20 to 30 and 30 to 40 represent 76% of the total number of SpaceX employees (Wise, 2023). According to a study in (Tyson, Kennedy and Funk, 2021) 71% of millennials and 67% of GenZ respondents said, climate should be a top priority to make the planet habitable for future generations. It can be concluded from this that SpaceX's young workforce has a high level of environmental awareness and therefore places great importance on sustainable corporate strategies, which in turn increases the focus on sustainable space missions and their impact on earth and space environment. This enables SpaceX to utilize the young workforce's commitment to sustainability to make space missions even more environmentally friendly.

3. **Analyzing how SpaceX's dynamic capabilities, including reputation management, adaptability, and agility, enable the company to remain at the forefront of space debris combat.**

Reputation management, adaptability and agility represent three dynamic capabilities which SpaceX uses for their business success and contribute to the sustainable use of space.

Reputation management: SpaceX's reputation being an innovative and responsible space company can facilitate to achieve competitive advantage. SpaceX has proven that by successfully reusing space objects increases stakeholder confidence and customer satisfaction due to the fact of full order books from clients like NASA. Transparency by unclosed communication of space debris population in different orbits, SpaceX sets a good example by increasing the transparency of this crisis, which in turn has a positive impact on its reputation. A good reputation leads to a high standing in society and in addition to the confidence of stakeholders. It increases the company's attractiveness for investors plus new highly qualified employees get enticed.

Adaptability is the competence of a company to proactively identify alterations and recognize opportunities in a fast-changing business world. SpaceX's ability to adapt to the rapidly changing space world was demonstrated with Starlink. In doing so, SpaceX managed to be the first to compete with traditional internet providers through satellite-based internet and has been expanding its market position ever since. The product process starting with the design phase to the final manufactured product, which is completely developed internal, allows SpaceX to quickly react to market trends, legal regulations, and customer requirements.

Agility repents a core capability of SpaceX to quickly react to unexpected shifts in product and service demand to accomplish competitive advantage. SpaceX pursues a stringent approach to vertical integration, enabling them to demonstrate high agility. Vertical integration refers to the practice in which companies bring all processes from concept to the final product internally together, less outsourcing more insourcing. In general, vertical integration relates to high costs and associated with risks, when implementing of vertical integration fails. By vertically integrating processes, the following levers lead to an increase in agility. Much less dependencies to suppliers reduce risks through supply bottlenecks created by a crisis, like Covid-19, or political tensions between the supplier country and SpaceX. Fast testing of newly developed space object components through different departments, which oversee designing and building one part. Changes of design or configurations can be managed in real time, which is achieved through internal communication between the departments, so changes do not have to be agreed with a supplier (Williams *et al.*, 2019). These facts enable SpaceX to rapidly test new demising materials, space debris avoiding designs and actively react to new regulations in the future.

Agility can also be applied to various missions, as SpaceX carries out rocket launches itself, enabling Starlink satellites to be replaced immediately after a mal function, so no dependencies on other space launching companies occur.

4. **Reviewing the specific eco-innovative capabilities SpaceX has demonstrated in its quest to reduce space debris. How can these strategies influence industry standards and contribute to a more sustainable approach to space exploration?**

This question aims to highlight the ecological strategies of SpaceX to secure earth and space environment. A distinction can be made between three different types to this framework, the eco process innovation, the eco product innovation and the eco organizational innovation.

Eco process innovation refers to the approach to improve existing production processes with goal of reducing environmental impact. As described in the paragraphs above, SpaceX is pursuing a vertical integration for reducing costs and avoiding supplier dependencies. But in the case of CO2 emissions, insourcing is also favorable compared to outsourcing, since less transportation is needed between SpaceX and suppliers, which leads to lower emissions due to fact of simply inhouse transportation. To further reduce the environmental impact of internal production processes, SpaceX could implement a lean manufacturing system for the whole production chain. This approach has the aim to maximize productivity and simultaneously minimize the waste within a manufacturing process. This strategy then could be introduced by legal authorities as a space industry standard to mitigate on earth debris creation.

Eco product innovation is the development of new or upgraded products with the aim of decreasing the environmental footprint within its product lifecycle. By improving the Starlink satellite design protecting critical components (such as batteries), selecting burnable materials and achieving a failure rate of only 1%, SpaceX significantly reduced the impact of its satellites missions on the space debris population. In addition, SpaceX's fast deorbiting strategy leads to a controlled product life cycle end and therefore poses little danger of collisions with the subsequent of newly created space debris. In addition, SpaceX's strategy of using low orbits has a great advantage. Non-maneuverable satellites get dragged to earth by gravitational pull and demise in the atmosphere.

Closing, Falcon 9's product lifecycle provides a significant advantage over the competition, as it re-enters in the earth's atmosphere in a controlled manner and lands on the ground. All other operators either leave theirs in orbit or perform deorbiting into the ocean.

Eco organizational innovation is the process of upgrading the management procedure of organizations through eco method practices. It includes eco learnings or the implementation of departments that deal with eco issues. SpaceX pursues a transparent information provision regarding current space debris population and its space debris avoidance maneuvers in LEO to the FCC. Since such information transfer is crucial for a sustainable space use. Legal authorities should grant preferences or rather privileges to space operators who demonstrate transparency with their data, serving as a substantial incentive for operators to uphold transparency. SpaceX could establish an internal department dedicated solely to external communications on the topic of space sustainability. This team could ensure that other space operators and spacefaring nations are further sensitized to this issue and that each party's knowledge can be shared to conduct future missions with less risk. SpaceX could lead the way through already sustainable missions to show the space industry that collaboration on knowledge transfer, space debris data and information on space debris avoidance maneuvers will help mitigate this crisis and that space is a common good to which each party must contribute.

7 Conclusion and Limitations

Underlying this master thesis is the creation of a case study for undergraduate and graduate students, to link theoretical management frameworks to the crisis of space debris and the business adaptive strategies of SpaceX to mitigate this greatly.

The case provides insights of the consequences through space debris on social, economic and ecologic sequence of events, with the focus on the private space company SpaceX and its strategies to mitigate newly created space debris. Compared to the covid-19 crisis, the space debris crisis is still in its infancy, but will bring exponentially increasing risks in the future to diverse factors as the number of space missions continues to rise. SpaceX's early focus on sustainability in space missions pays off along with cost reductions to grant a competitive advantage in the future and are ahead of the curve with their strategies, enabling them to act as initiators for legal foundations in relation to space debris avoidance.

The strategies SpaceX pursues to address the crisis are versatile, innovative, and cost-orientated, which is why an evolution of SpaceX from a key player to a leader in the industry in sustainable space operations was traced. The major key take aways of the study was foresight, technical in-house know-how, cost advantages and adaptability SpaceX has achieved to be on the forefront addressing the space debris problematic.

As mega constellations such as Starlink are becoming increasingly popular, legal requirements should be drafted soon to regulate the number of satellites in mega constellations from different provider and specify certain technical requirements to avoid collisions with the consequence of newly created space debris.

While this master thesis created insights into the interaction between SpaceX's adaptive strategies and the space debris, limitations should be mentioned here that could affect the interpretation. Firstly, the reliance on only secondary data could set up potential constrains to the main findings. Interviews with SpaceX professionals focusing on space sustainability can be leveraged to direct perceive internal data on the topic and SpaceX's strategic directions in the future. Secondly, due to the volume limitation of this thesis, some details, like geopolitical aspects, were not taken in consideration as they would have exceeded the research objective but play a pivotal role in the space debris crisis and need to be investigated for further research.

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