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BUSINESS ASPECTS OF SPACE TRANSPORTATION SYSTEMS DEVELOPMENT

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TABLE OF CONTENTS

INTRODUCTION **1**

1 SPACE INDUSTRY OVERVIEW **3**

1.1 Space Industry Markets 4
1.2 Space Industry in the European Union 5
1.3 Launcher System Sales 8

2 COMMERCIAL SPACE INDUSTRY **8**

2.1 Commercial Space Industry Structure 9
2.2 Role of the ISS and NASA in the Commercial Launch Industry Development 11
2.3 Commercial Market 12
2.4 Commercial Launches 14

3 SUPPLY CHAIN MANAGEMENT AND LOGISTICS **16**

3.1 Space Sector Supply Chain 17
3.1.1 Supply Chain Structure 17
3.1.2 Value Chain 18
3.2 Space Logistics 20
3.3 Reverse Logistics 22

4 OPERATIONS AND LAUNCH VEHICLES **25**

4.1 Basic Operations 25
4.2 Orbit Types 27
4.3 Space Launch Vehicles 27
4.3.1 Space Launch Vehicle Types 28
4.3.2 Number of Stages 29
4.3.3 Space Transportation Vehicle Parts 31

5 SPACE TRANSPORTATION SYSTEM FINANCING AND CONTRACTING **33**

5.1 Financing of Space Projects 33
5.2 Contracting 34
5.3 Risk Management 35
5.4 Insurance 36

6 SPACE TRANSPORTATION SYSTEM COSTS **37**

6.1 Spaceflight Cost Overview 38
6.2 Cost Estimation Methods 41
6.3 Comparison of Reusable and Expendable Launch Vehicles 41
6.4 Cost of Reusable and Expendable Launch Vehicles 43
6.5 Dual Pricing and Cost Environment 46

7 FUTURE DEMAND PREDICTIONS **49**

7.1 Existing Markets 49
7.2 Emerging Space Markets 51
7.2.1 Space Tourism 51

7.2.2 On-Orbit Satellite Servicing 52
7.2.3 Private Space Exploration 52
7.3 Suborbital Reusable Transportation Systems 53
7.4 Space Launch System (SLS) 54
7.5 Skylon 55
8 QUALITATIVE RESEARCH OF SPACE TRANSPORTATION SYSTEMS 58
8.1 Interview Details 58
8.2 Cost and Revenue Specifics 58
8.3 Reusability as a Sustainable Future Approach 62
8.4 Space Industry Development and Demand 63
CONCLUSION 68
REFERENCE LIST 70

LIST OF FIGURES

Figure 1. Distribution of Sales by Main Market Segment (%) 6
Figure 2. Sales by Main Market Segment: Military vs. Civil (M€) 7
Figure 3. Sales by System: Public vs. Private customers (M €) 7
Figure 4. Launcher System Sales (M€) 8
Figure 5. Total Commercial Space Launches from 1990-2014 10
Figure 6. Sales to Commercial Market by Customers (%) 13
Figure 7. Sales on the Commercial Market by System (M €) 13
Figure 8. Number of Orbital Commercial Space Launches in the Timeframe 2005 – 2014 ... 14
Figure 9. Orbital Commercial Space Launch Revenue 15
Figure 10. Supply Chain Network 16
Figure 11. Satellite Applications Value Chain 19
Figure 12. Space Activities Value Chain 20
Figure 13: Launch Vehicle Cost and Weight by Major Element 24
Figure 14. Eccentricity of Orbit indicating deviation from a Perfect circle 26
Figure 15. Orbital Inclination Presenting an Angle Between the Plane of an Orbit and the Equator 26
Figure 16. Comparison of Single-stage and Two-stage Launch Vehicles 30
Figure 17. Ariane V Cut-away 32
Figure 18. Ratio of Successful Mission to Total Number of Mission from 1957 till 2008 35
Figure 19: Production Cost and Selling Price of a New Aircraft Model 39
Figure 20. Technology "S" curve depicting the need to transition to a new space access paradigm 43
Figure 21. Cost per Launch vs. Average Launch Rate from 2001- 2015 46
Figure 22. Domestic and International Launch 1999-2004 48
Figure 23: Distribution of Forecasted Launches by Payload Segment and Vehicle Size 49
Figure 24. Commercial NGSO Launch History and Projected Launch Plans 50
Figure 25. Price Elasticity of Suborbital Tickets for Individuals with $5 million in investable assets. 54
Figure 26. Comparison of Current Launch System Business Model with Airline Business Model 56

Figure 27: Cost Comparison of Skylon and Falcon Launch Vehicles 57
Figure 28: Launch Vehicle Capacity in Relation to Price per Kilogram 59
Figure 29: SpaceX Earnings 60
Figure 30: NASA Awards in Millions of € 61
Figure 31: SpaceX Launch Prospects 61
Figure 32: Venture Capital Investment in Space 65
Figure 33: Mass Launched (kg) by Public/Private Customers 66

LIST OF TABLES

Table 1. Final Sales by Main Customer Segment (M €) 5
Table 2. Final Sales by Main Product Segment (M€) 6
Table 3. Forward and Reverse Logistics Comparison 22
Table 4. Fixed Price vs. Cost Plus Fee 34
Table 5. Comparison of Expendable vs. Reusable Launch Factors 45

INTRODUCTION

Transport is movement of people or goods from one point to another (Transportation, 2016). This can be performed by multiple means of transport such as land, maritime, rail, or air transport. Each of the mentioned has its advantages and disadvantages, depending on what we transport (Meixell & Norbis, 2008, p. 183). In this thesis, I will focus on another, less common mode of transport, namely space transport. This mode of transport is not commonly mentioned in the literature as one of the transportation modes of our time, mostly because it is still not very commercially developed and used by individuals directly in everyday lives.

There are many applications that would not be possible without space transport, such as Global Navigation Satellite Systems (hereinafter: GNSS), weather monitoring and forecasting, science conducted in space, communication networks across the globe and many others. With technological developments, number of applications that require transport to space is growing and the importance of space transportation industry with it. The biggest obstacle to this development is still the enormously high costs of reaching orbit. However, the wave of new commercial companies getting involved in the space industry might be able to overcome this barrier (Scalinger, 2013). Recently awarded contracts for commercial resupply missions to the International Space Station (hereinafter: ISS) show that private industry is up for the challenge.

Development of new reusable launch vehicles might be the solution to reduce transportation costs per pound to orbit. Whether reusable or expendable vehicle is better in terms of cost optimization is a complex issue. Many different categories of reusable systems exist, which differ in reusability level, number of stages and other properties. Furthermore, there are multiple ways of recovery such as landing pads, runways, catch nets or the ocean. There are arguments supporting both expendable and reusable options. On the one hand, expendable launch vehicles require expensive components each time they are built compared to reusable launch vehicles, where components can be reused multiple times. On the other hand, expendable vehicles achieve economies of scale as they are produced in larger quantities. Moreover, the simplicity of design is also a factor driving down the first unit costs and recurring manufacturing costs. With reusable launch vehicles, design becomes more complex (adding landing gear, additional weight, etc.) and drives the costs up. Lower costs might be achieved with a higher number of launches, depending on systems life cycle time and development costs (London, 1994, pp. 118-122). Expendable unmanned launch vehicles are currently most common worldwide. This has been the case throughout the history of spaceflight.

New, innovative companies like Space Exploration Technologies (hereinafter: SpaceX) are changing the industry. SpaceX recognized the potential in cost reduction and decided to design and manufacture their launch vehicles in-house from the ground up. It is the first private company to transfer cargo to and from the ISS and return safely to the Earth. Their

vehicles continue to supply the ISS and engineers are also developing crew modules for the near future. Multiple other private companies are also joining the commercial spaceflight competition, aiming at various niche markets (SpaceX, 2015).

Federal Aviation Administration (2015, p. 51) forecast projects 986 payloads to be launched commercially from the year 2015 to 2024. This would be done with 131 launches to orbit with multiple payloads on one launch. In addition to orbital launches, suborbital reusable vehicles are creating new demand in the spaceflight industry. The companies aim at high flight rates and relatively low cost. Both orbital and suborbital options aim for demand of multiple markets such as science and education, satellite deployment, basic and applied research, remote sensing, commercial human spaceflight, resupply missions, aerospace technology testing and other to be generated in the future (Tauri Group, 2012).

The purpose of this master's thesis is to evaluate the current state of space transportation industry, analyse the factors affecting space transportation systems development, and try to find the main possible solutions for cost reduction and expansion of space transportation activities.

Goals of this research are:

- To identify the main parts of the space industry and understand how its supply chain works.
- To analyse cost drivers of space transportation.
- To find advantages and disadvantages of reusable and expendable space launch systems.
- To analyse potential areas of future demand.
- To predict the most probable future development of commercial space industry by means of analysed data.

Methodologically, I will use the secondary resources mostly. It will include desktop research of past analyses, different private companies, governmental agencies and historical industry data. Various case studies from the past will be used as well as publications and company reports of conducted tests and trials. I will also acquire the primary data by interviews conducted with industry professionals.

In the first part, I will briefly describe space transportation history, important events, and explain the purpose of this thesis. The main focus will be on space industry markets and product sales. In the chapter to follow, commercial space industry and its market situation will be discussed. Topics will include the cooperation of private companies with the government, as well as the importance of international projects in the development. Definitions of the main subjects connected to supply chain management, logistics and transportation in general will follow. Furthermore, an overview of the space industry, its supply chain, major stakeholders and its value chain will be done. In the next chapter, I will take a closer look at space

transportation operations, infrastructure, and vehicles that are used for transport of cargo and people to and from orbit. Vehicle technical properties, performance, and economic indicators will be discussed. In addition, different types of orbits depending on client's requirements will be explained. Following operations and launch vehicles, I will move to financing and contracting part. This is a very important topic, as it is one of the major factors affecting space transportation systems development. In this chapter I will explain types of contracts and how space projects are financed, what kind of risks are connected to it, and some details on how it is mitigated with insurance.

With the basic understanding achieved, I will continue with the costs analysis. In this part, I will analyse various cost factors, starting with historical examples to today's cost estimations. Different cost estimation methods will be explained. Moreover, comparison of reusable and expendable vehicles will also be included as this is one of the biggest debates regarding cost efficiency in the future. As the last topic of this chapter, I will also focus on the partnership between private and public sector and explain its importance.

The following chapter will mostly focus on the future of the industry. Predictions regarding existing and new potential market demand will be discussed, as well as different future space transportation system concepts, which are currently being developed. The final chapter includes interviews with 6 industry professionals, where main issues of today, possible solutions, and the outlook of space transportation systems future will be discussed.

1 SPACE INDUSTRY OVERVIEW

The space industry is slowly changing from government dominated industry to more balanced one including private companies. However, if access to space and demand are very limited, the industry cannot scale. Unique nature of space business industry should be considered to create a viable business (Gortuna, 2013, pp. 1-3). Some differences can be attributed to the challenging space environment, and some to the historical factors that include strong military rationale. Nowadays, national pride still has its role in the industry, but justification of investment and returns have a larger role than in the past (Gortuna, 2013, p. 10).

Using functional view, space activities can be divided into military, civilian and commercial. Each category has different motivation for its activities. Military space activities are mostly used for national security purposes, and were the first ones involved in space. In the Western countries, they include the Army, the Navy and the Air Force. The Soviet Union did not separate military and civilian activities. Being a socialist state, it also excluded commercial activity. Official existence of the U.S. space program started in 1958 when National Aeronautics and Space Administration (hereinafter: NASA) was created to take over the civilian space activities that became separated from military. Civilian space programs are intended for the public good, but often it is difficult to separate between military and civilian

activities. Some programs can be run by military, but then serve civilian purposes and vice versa (Johnson, 2007, p. 151).

1.1 Space Industry Markets

Market demand overestimates in the space industry are very common. This happens in the government sector, as well as in private one. For example, future estimates of commercial communication satellites were overstated in 1980's. Estimates were based on advent of direct broadcast TV services that were supposed to be available in 1990's, but actual growth started about 5 years later. This was not the only inaccurate market prediction. In the 1970's, NASA sponsored different studies, from potential new uses of space to macroeconomic analyses of technological impact on the economy. The results pointed to growing demand for space related goods or services. All of them stated NASA as the client and included optimistic presentation to justify continued research and development (hereinafter: R&D) funds for NASA's activities (Hertzfeld, Williamson, & Peter, 2005, pp. 5-6).

The United States of America (hereinafter: the USA) have a rich history of space flight in cooperation with commercial industry. In the beginning, the government was the main customer and operator due to high cost and risk, with companies being the ones to develop, engineer, and manufacture high quality products. The industry traditionally worked under governmental direction, final decisions making and responsibility. This led to suggestions that past space efforts were more accomplishments of the private industry than the government. This is partially true as far as system design, testing and manufacturing goes. However, the government had its role in system requirements, acceptable design implementation, managing risk and execution (Federal Aviation Administration, 2010, p. 8).

Spaceflight and space activities made several new technology developments which had significant impacts in different industries, such as digital imagery enhancement, which is now used in medical applications, fireproof spacesuit materials, which is now used by fire departments, astronaut food testing, which had an impact on food testing worldwide, and many more. These spinoffs have frequently been mentioned as one of the reasons for funding the space program (Johnson, 2007, p. 143). Products manufactured by the aerospace industry are made to experience the extreme conditions of our environment (temperatures, acceleration, radiation etc.). To create them, special expertise is required and a lot of precision, attention to detail, and testing of parts by long, multi-tiered supply chain. All the mentioned must be accomplished while maintaining high standards of safety, reliability, security, quality and sometimes cost control (Near Earth LLC, 2009, p. 6).

Most products are priced to reflect the cost of investment, production and marketing. Decision making is performed by analysing supply and demand conditions signalled through the price mechanism. Space industry has always been influenced by governmental policy and decision-making. Market economics have been affected by defence, security and politics. In the launch

vehicle sector, public and private investments are mostly determined by government R&D budgets. Many operational activities are often performed by the government or company that is under governmental contract. Competition is present, however, in the form of oligopolistic bidding for government and private launch contracts, where price is often not the most important factor (Hertzfeld et al., 2005, p. 3).

1.2 Space Industry in the European Union

Space manufacturing industry designs, develops, and manufactures spacecraft and launchers, and is at the higher end of space value chain. It is also involved in ground systems and operations. The sector is highly capital intensive. In Europe, space sector is distributed across the European Space Agency (hereinafter: ESA) member states, and is highly concentrated with the two major holdings dominating the industry. These are the Airbus Group and the Thales. They represent more than half of total space industry in Europe (ASD – Eurospace, 2014, p. 5).

In 2013, European space industry delivered 24 spacecraft to the launchpad and produced 5 launchers for operations in Kourou, where it primarily executes its space launches. In the same year, it generated 6,815 million euros in sales. It has a large domestic market and it also exports its products to public and private customers worldwide (ASD – Eurospace, 2014, p. 5). The estimated market demand for launches is usually higher than the actual launches, due to satellite technical issues, launch vehicle technical issues, weather, range availability issues, dual-manifesting, business issues, regulatory issues, or geopolitical issues, to mention some of them (Federal Aviation Administration, 2015, p. 18). The Table 1 shows that final sales have a steady growth through time, as well as other categories, except European private customers. There is also a large difference when comparing European customers and customers from the rest of the World (RoW). European customers dominate in all the categories.

Table 1. Final Sales by Main Customer Segment (M €)

Category	**2011**	**2012**	**2013**
Final sales (in M €)	6,375	6,555	6,815
European public customers	3,438	3,421	3,541
European private customers	1,662	1,702	1,526
Other European customers	84	105	168
Public customers RoW	387	499	660
Private customers RoW	778	790	864
Other customers RoW	26	38	57

Source: ASD – Eurospace, *The European Space Industry in 2013*, 2014, p. 5.

Space manufacturing sector can be divided in 4 different business areas. First, there are design, development and manufacturing of satellites. Second, there are launchers, and third, there are ground systems and services, followed by the scientific systems. The Table 2 shows the sales numbers for each business area through the years. The most dominant segment is satellite application systems, which is far ahead of others. However, it remains almost stagnant through time (ASD – Eurospace, 2014, p. 5).

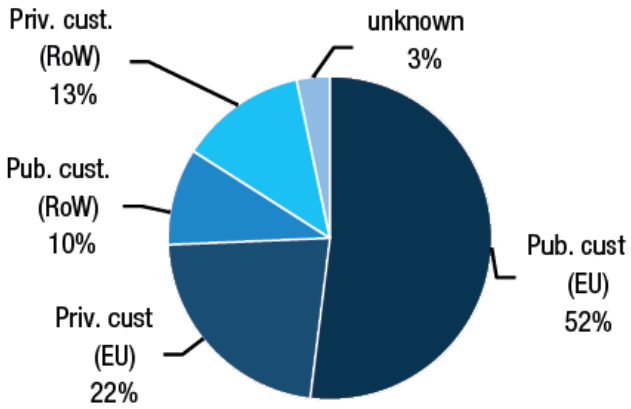
Table 2. Final Sales by Main Product Segment (M€)

Category	**2011**	**2012**	**2013**
Final sales (M €)	6,375	6,555	6,815
Launcher systems	1,193	1,308	1,447
Satellite applications systems	3,233	3,385	3,370
Scientific systems	951	1,086	1,084
Ground systems and services	877	734	795
Other & Unknown	120	42	120

Source: ASD – Eurospace, *The European Space Industry in 2013*, 2014, p. 5.

The Figure 1 graphically represents the main market segments sales distribution of the European space industry worldwide. We can clearly see the dominant domestic public market with 52 per cent market share, followed by the domestic private market.

Figure 1. Distribution of Sales by Main Market Segment (%)

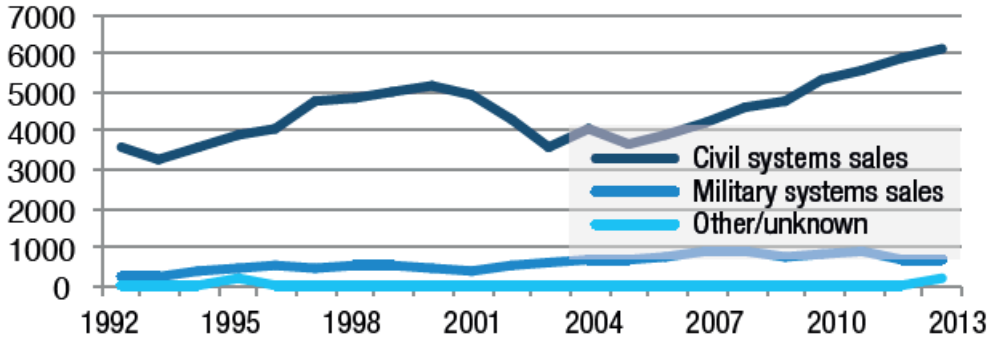


Source: ASD – Eurospace, *The European Space Industry in 2013*, 2014, p. 6.

To evaluate defence/military component of industry sales, division of systems, civil and military nature is required. Due to complex nature of space programs and innovative

procurement schemes, there are also cases where military systems are procured by civil customers. This is mostly the case in space superpowers including Russia, the USA, and China. Europe has very limited investment in military space systems and they are only a fraction of the industry revenues as illustrated in the Figure 2 (ASD – Eurospace, 2014, p. 7).

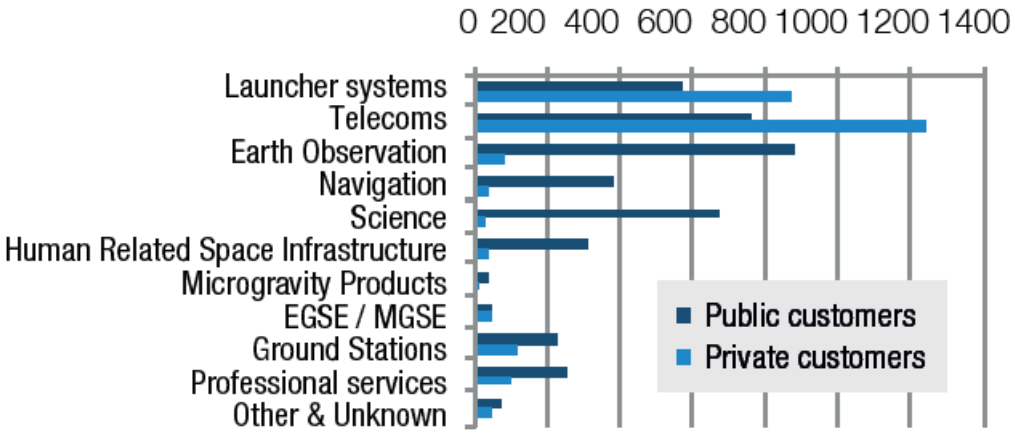
Figure 2. Sales by Main Market Segment: Military vs. Civil (M€)



Source: ASD – Eurospace, *The European Space Industry in 2013*, 2014, p. 7.

Due to the nature and structure of commercial space markets, European sales to private customers are focused on large geostationary telecommunication satellites and operational launch systems, which are the two main product groups. Since the late 1990s, low Earth orbit (hereinafter: LEO) mobile communication satellites (constellations) and commercial Earth observation systems markets have additionally emerged (ASD – Eurospace, 2014, p. 10).

Figure 3. Sales by System: Public vs. Private customers (M €)



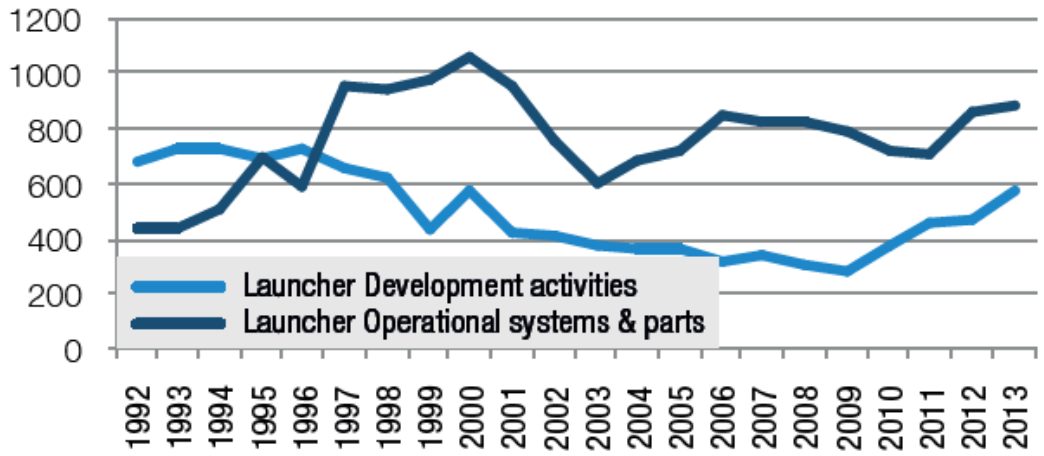
Source: ASD – Eurospace, *The European Space Industry in 2013*, 2014, p. 10.

Public customers dominate in most of the categories. However, private customers are ahead in launcher systems and telecommunication categories which are the largest sales generators, followed by the Earth observation category.

1.3 Launcher System Sales

Focusing on launcher systems brings us to the main European space industry launchers. These are the Ariane and the VEGA. The programs include two different market segments which are complementary to each other (ASD – Eurospace, 2014, p. 14). The market can be divided into operational launcher systems and launcher development activities, which is illustrated in the Figure 4.

Figure 4. Launcher System Sales (M€)



Source: ASD – Eurospace, *The European Space Industry in 2013*, 2014, p. 14.

Operational launcher systems include European space industry production and integration of the Ariane and the VEGA launch systems for the Arianespace. It is focused on domestic market although the Arianespace works globally. The industry also exports certain parts that are later integrated to non-European launchers (ASD – Eurospace, 2014, p. 14). There is a growing activity in the private sector for launch vehicle development and operations. In the next chapter, commercial space industry will be examined further.

2 COMMERCIAL SPACE INDUSTRY

The concept of private spaceflight has been around since 1965, when the first commercial satellite called Early Bird went into regular revenue service. Since then, the private sector has expanded beyond anything people could imagine 50 years ago (Velocci, 2012, pp. 49-51). There were two developments in 1980's that began to move the space launch industry from governments to the commercial sector. The first one was the European launch vehicle Ariane,

which was structured as a private enterprise while still subsidized by ESA and the French government. The second one was the loss of Space Shuttle Challenger in 1986. This event made the USA realize, it is dangerous to rely only on one type of a launch vehicle. They stimulated private industry launcher development and approved larger orders of expendable launch vehicles (hereinafter: ELV), stimulating companies to take advantage of economies of scale. Governments remained the major customers, with private companies encouraged to bid for government launch contracts. The industry remained far from truly commercial due to reliance on government and high level of regulation. However, the structure that permits and encourages private sector activity was created (Hertzfeld et al., 2005, p. 9).

2.1 Commercial Space Industry Structure

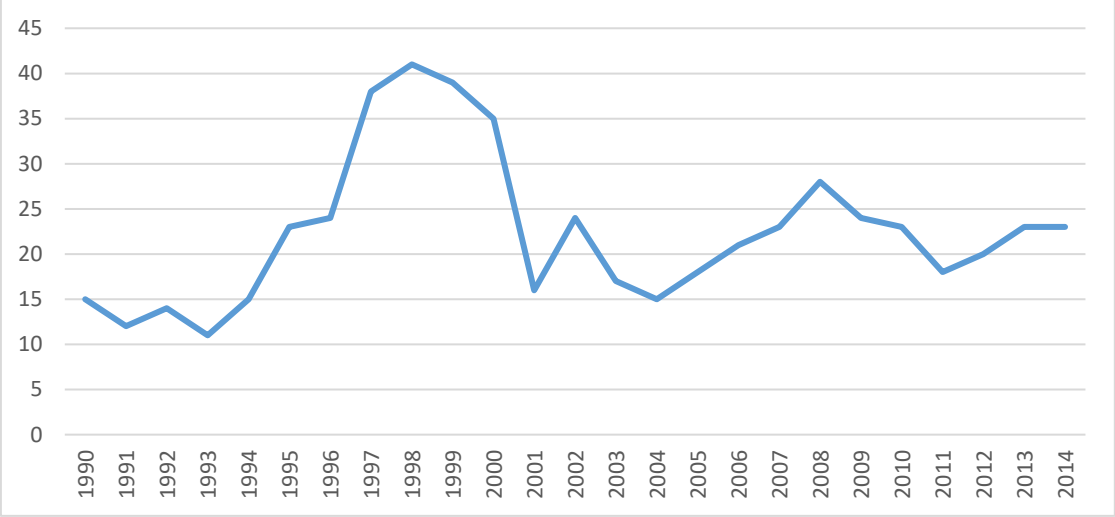
Today, the commercial space industry is a very important part of telecommunication industry, financial markets, and other critical sectors. Many new advances in propulsion technology and aerodynamics have occurred with technological advances that can be applied to commercial space ventures. Years of private company's cooperation with the government gave them the required knowledge and know-how to develop their own systems. Government will still take the lead in some areas of the space industry and continue to develop public-private partnership. Many new space ventures sound very ambitious. However, they find increased credibility and acceptance by investors (Velocci, 2012, pp. 49-51). Commercial space launch industry generates more than $250 billion in revenue annually (Dillow, 2016)

In the space launch industry, any launch that is up for bid is defined as commercial even if the launch provider (supply) and satellite owner (demand) are owned by the government. Commercial often stands for competed and not necessarily private (Johnson, 2007, p. 153). Commercialization of space is most evident in the USA. However, the ESA and its member states are also moving towards passing more activities to the private sector. This includes Earth imaging, commercial communication services, and launch and crew support, to name a few (Velocci, 2012, p. 52).

Since the early days of the space age, private sector companies served the government as contractors, mostly fulfilling governmental, civilian and military needs, which were mostly motivated by the race between the Soviet Union and the USA. Since the beginning of 1990's, public funding has decreased while private investments have taken off. As it can be seen in the Figure 5, there were some events that disrupted the growth, such as the dot.com bubble burst and the September 11th attacks in 2000s. Despite these events and the recession of the year 2008, launches remained at a steady level (Gortuna, 2013, p. 50). The peak of commercial launch events happened in 1998, with 41 launches. This happened at the height of dot.com boom. Most of the demand for these launches came from the LEO telecommunication constellations. The entire Iridium satellite constellation (66 satellites plus spares) was launched in a period of 13 months (Gortuna, 2013, p. 51). Some additional statistics for the year 2016 show that the number of commercial launches amounted to 21,

which represents 25 per cent of the total 85 launches. The USA performed 11, Europe 8 and Russia followed with 2 commercial launches (Messier, D., 2017).

Figure 5. Total Commercial Space Launches from 1990-2014



The strategy of using commercial space transportation instead of traditional government lead has many benefits. One of the main ones is cost effectiveness, which was demonstrated through NASA's commercial cargo program. For this to work, it is important that government is not the only customer (National Aeronautics and Space Administration, 2011, p. 5).

Although the concept of commercial crew and cargo transportation systems has been around for decades, in the USA much was changed in 2004, with the final report of Presidents Commission on Implementation of the US Space Exploration Policy recommended the following to NASA: "NASA recognize and implement a far larger presence of private industry in space operations with the specific goal of allowing private industry to assume the primary role of providing services to NASA, and most immediately in accessing LEO". Developments continued in 2005 with NASA's Commercial Orbital Transportation Services (hereinafter: COTS) project. This was a stimulation effort for the industry to develop a safe, reliable and cost-effective space transportation system. Furthermore, commercial crew development program was formally endorsed in the NASA Authorization Act of 2010, signed by the president (National Aeronautics and Space Administration, 2011, p. 6).

Another huge milestone for the commercial space industry occurred in December 2010, when company SpaceX successfully launched a vehicle to orbit and separated the space capsule, which completed two full Earth orbits and safely landed in the Pacific Ocean (National Aeronautics and Space Administration, 2011, p. 30). Developments continued with the first identifiable "routine" commercial space market, the resupply of the International Space Station (hereinafter: the ISS). Commercial efforts have proven very successful with a large

cost reduction (National Aeronautics and Space Administration, 2011, p. 31). The ISS played a major role in the development of commercial space industry.

2.2 Role of the ISS and NASA in the Commercial Launch Industry Development

The ISS, a partnership project between the USA, Russia, Europe, Japan, and Canada, with 15 other nations involved in design, assembly and research, serves as a starting point for commercial space launch industry development. It is the most complex international engineering and scientific project and the largest structure operated in space (NASA Office of the Chief Technologist, 2014, p. 5). Resupply missions are of great importance for the ISS operations. Since the beginning, government has operated missions and carried out the resupply. Commercial resupply operations were the next logical step as the private sector is much more efficient in performing routine operations. With the successful public-private partnership, it was a major factor to start the new era of commercial spaceflight (Commercial Resupply Services Overview, 2016).

Commercial efforts extensively started when NASA announced its COTS program, focused on development of commercial cargo transportation systems. Under this program, SpaceX developed its intermediate Falcon 9 launch vehicle and Dragon spacecraft, as well as Orbital Sciences Corporation its Cygnus spacecraft and medium-class Antares launch vehicle. In 2008, NASA awarded Commercial Resupply Services (hereinafter: CRS) contracts to SpaceX and Orbital. The contracts included $1.6 billion SpaceX contract for 12 flights through 2015, and $1.9 billion Orbital contract for 8 flights during the same period. Following the CRS, NASA continued with Commercial Crew Development program called CCDev in 2010. Award recipients were Blue Origin, Boeing, Paragon Space Development Corporation, Sierra Nevada Corporation and United Launch Alliance. In 2011, NASA continued investing in commercial crew transportation with the CCDev2 program in which Blue Origin, Boeing, Sierra Nevada Corporation, and SpaceX won awards totalling $315 million. In 2012, NASA continued its support to commercial space transportation industry with Commercial Crew Integrated Capability program, which was the next phase of commercial crew development. The expected result of this program is the maturation of commercial crew transportation systems. Boeing, SpaceX and Sierra Nevada Corporation won award of more than $1.1 billion in total (Federal Aviation Administration, 2015, pp. 44-46).

Currently, NASA purchases ISS cargo resupply deliveries from two commercial companies, Orbital Sciences Corp. and SpaceX. Missions are designed for cargo delivery to the ISS, unneeded cargo disposal, and return of various cargo including research samples back to the Earth. Contracts have been signed for missions till 2020 with a possibility of extension till 2024 (NASA Awards International Space Station Cargo Transport Contracts, 2016). After the retirement of the Space Shuttle, this is a very good opportunity for opening the ISS to greater private sector involvement in resupply missions. It is a part of the innovative Commercial

Cargo and Crew program by NASA. The aim of this program is to reduce the costs of transportation to orbit and expand commercial market transportation independent of NASA's activities. Since all the space activities require transportation to space, this program is a huge enabler of further economic development. It is similar to historical road, rail and canal national infrastructure development investments (NASA Office of the Chief Technologist, 2014, pp. 6-7).

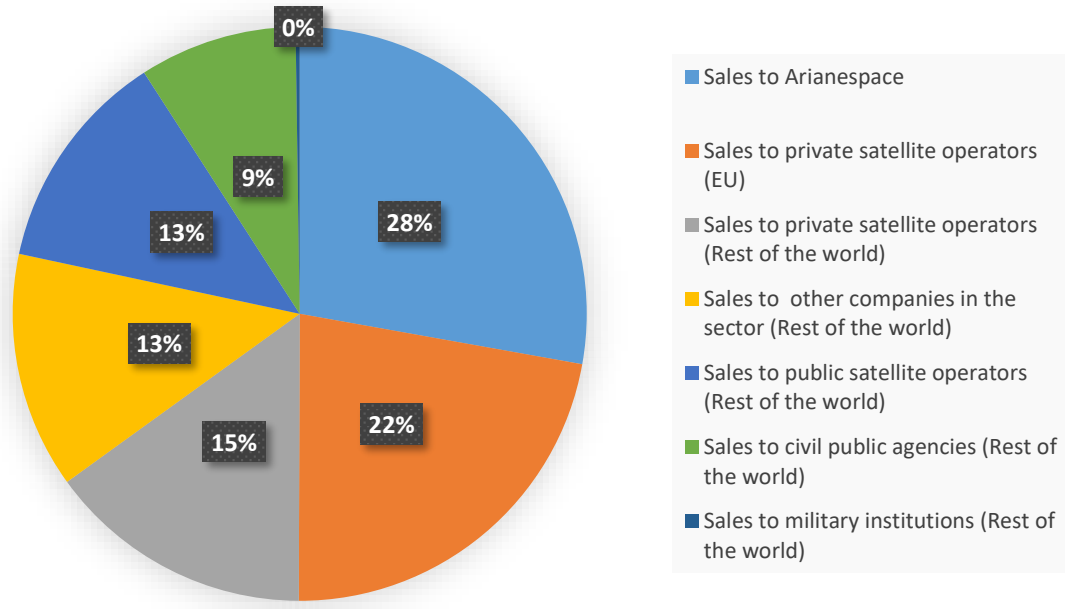
2.3 Commercial Market

For very complicated and capital-intensive projects, such as spaceflight, there must be a government support, at least in the beginning. A commercial market starts to expand once sufficient demand meets the available supply and creates a cycle in which producers can achieve economies of scale and consequently price reduction. Additional demand is usually expected once the prices decrease. The early customers bear the higher cost and are less price-sensitive. In some cases, the market never grows due to high costs or technological limitations, and remains in a small segment. In general, the major challenges of new market entrants in the commercial space flight market are the very high technical, financial and economic barriers. Furthermore, the market still has many uncertainties for the future. The industry sees initial investment size and lack of sufficient market size as the two largest obstacles for a viable commercial space flight industry. If expenditures were limited to recurring costs without large debt burdens, many companies are confident they would succeed. They believe that over time, they can include new market segments by achieving efficiencies which can lower the recurring costs. Current feeling of constraint is caused by small known market resulting in uncertainty of investment payback (Federal Aviation Administration, 2010, pp. 10-11).

Analysing commercial space sector revenues shows some interesting factors regarding demand trends. The most revenue is generated with satellite applications segment, in which 84 per cent is represented by satellite telecommunications. The second largest revenue is in navigation services, which have grown due to location – the importance of based services increases. The last one is the Earth observation segment, which accounts for approximately 1 per cent of total commercial sales, and is a relatively mature sector of the space industry (Gortuna, 2013, p. 15).

In the European space industry, European institutional customers represent the main revenue generating segment. However, the industry has added new private and public customers. According to the ASD – Eurospace (2014, p. 11) report, European commercial market can be defined as all sales to private entities plus all exports (sales to non-European customers). From the Figure 6, reliance on Arianespace for commercial market can clearly be seen. We can also see that military institutions present only a fraction of commercial market customers.

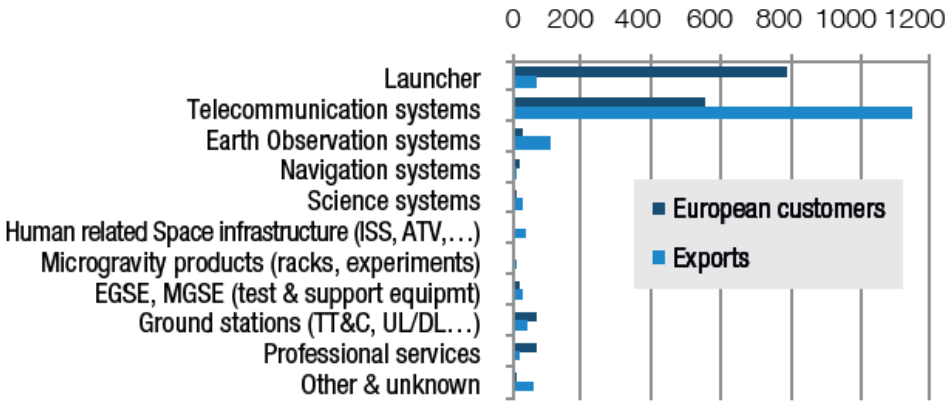
Figure 6. Sales to Commercial Market by Customers (%)



Source: ASD – Eurospace, *The European Space Industry in 2013*, 2014, p. 11.

Compared to European institutional market, which has distribution of sales among variety of systems, commercial market sales are mostly represented around launchers and communication systems as illustrated in the Figure 7 (ASD – Eurospace, 2014, p. 11).

Figure 7. Sales on the Commercial Market by System (M €)



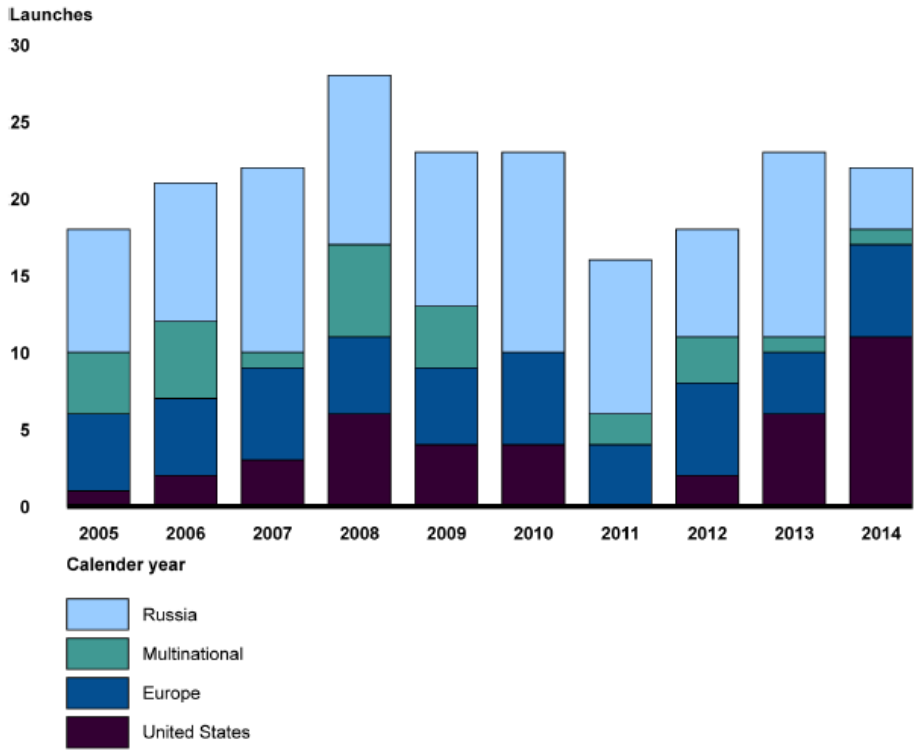
Source: ASD – Eurospace, *The European Space Industry in 2013*, 2014, p. 11.

The dominance of telecommunication systems and launchers can clearly be noticed, with launchers accounting for 28 per cent and telecommunication systems for 55 per cent of commercial sales. Exports of telecommunication systems present 37 per cent of European space sector sales in the commercial market (ASD – Eurospace, 2014, p. 11).

2.4 Commercial Launches

The Figure 8 shows that the USA has conducted fewer total orbital commercial launches in the last decade than Russia and Europe. However, they have increased the numbers in the recent years (Federal Aviation Administration, 2015, p. 17). We can see that Russia was the most dominant in the past but was overtaken by the USA and Europe in the year 2014. Variation of multinational projects can also be seen through years, which can be a result of relationships between countries and industry economic factors.

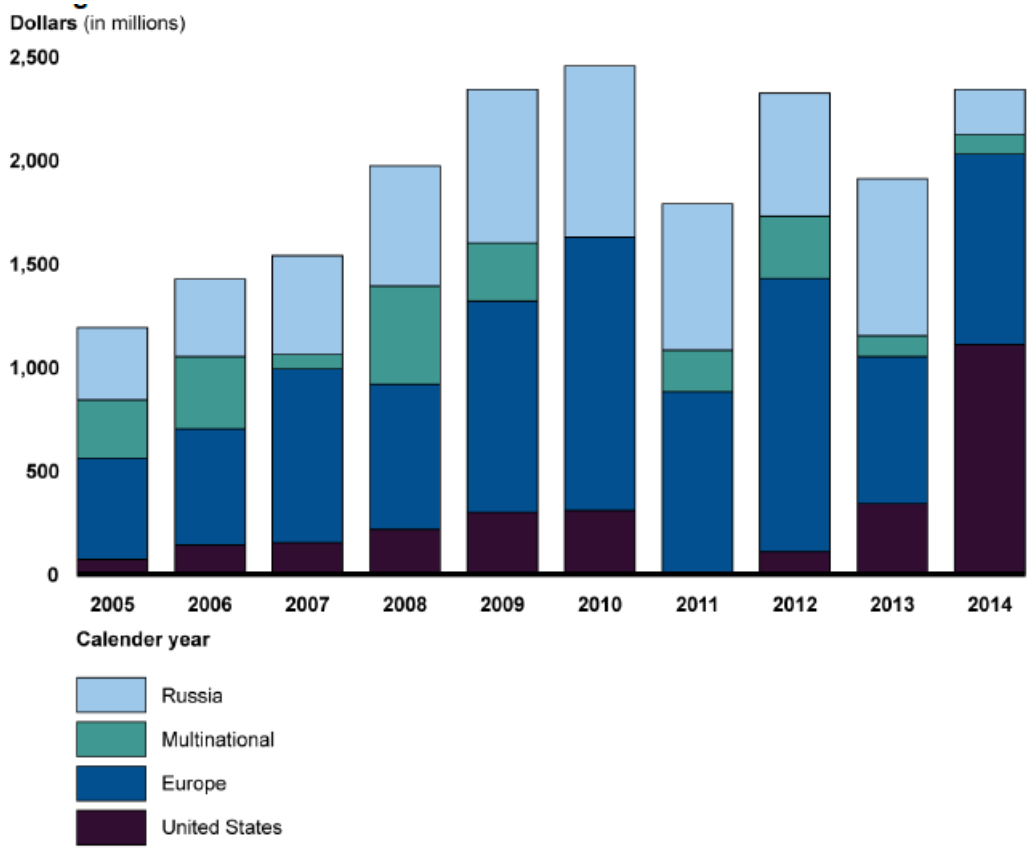
Figure 8. Number of Orbital Commercial Space Launches in the Timeframe 2005 – 2014



Source: Federal Aviation Administration, *2015 Commercial Space Transportation Forecasts,* 2015, p. 17.

Similar situation can be seen in the Figure 9, when comparing orbital commercial space launches by revenue. The USA is behind Russia and Europe, except in the year 2014. However, Europe generated more revenue with less launches than Russia.

Figure 9. Orbital Commercial Space Launch Revenue



Source: Federal Aviation Administration, *2015 Commercial Space Transportation Forecasts*, 2015, p. 18.

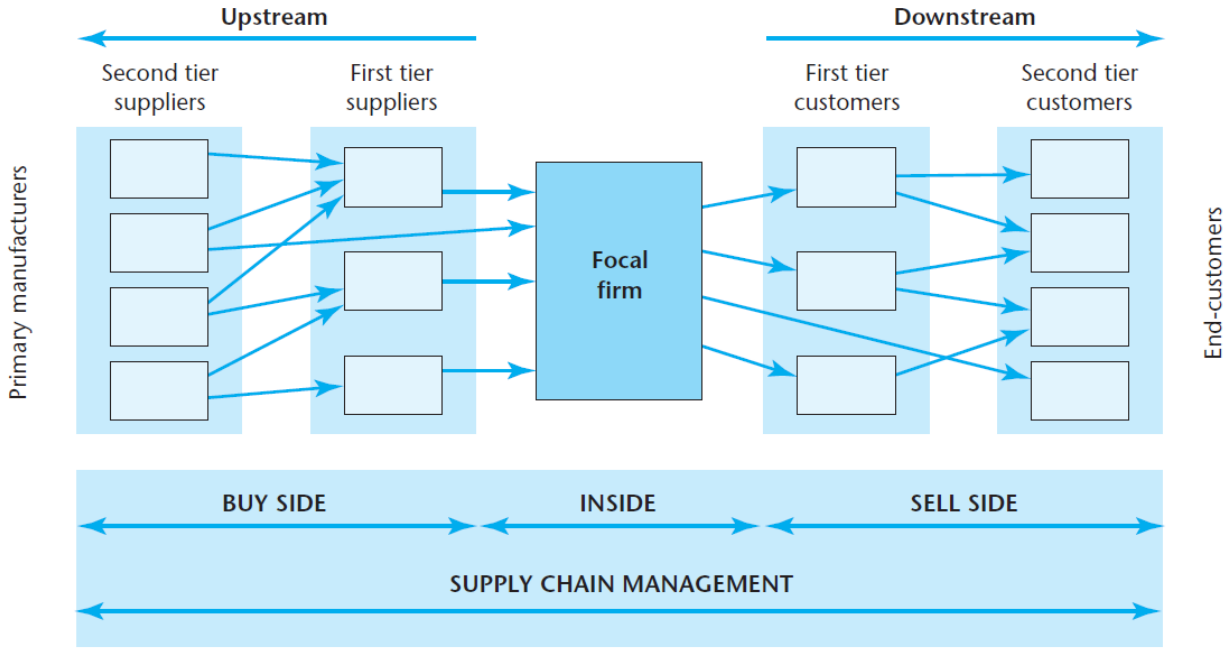
The recent increase in the USA launch numbers and revenue is due to different factors such as federal government contracts (NASA's commercial cargo program), SpaceX price competitiveness, and the emergence of space tourism industry and small satellite industry (Federal Aviation Administration, 2015, p. 19). Although the USA had more launches in 2014 and after, revenue was very close compared to Europe with both nations reaching almost $2 billion (Messier, D., 2017).

Commercial launch vehicle market is different from commercial market for most goods and services. Resources are not allocated according to supply and demand conditions, which is why the market does not respond predictably to price changes. Furthermore, due to government subsidies, competition is often not "free and open". Launch vehicle industry must deal with government regulation, subsidies, defence and civilian customers to a much greater extent than other industries. The nuclear power industry comes closest to the commercial launch industry. Nevertheless, its commercial business practices have been around longer and many trade issues have already been resolved (Hertzfeld et al., 2005, p. 11). To better understand the space industry, its supply chain structure needs to be analysed.

3 SUPPLY CHAIN MANAGEMENT AND LOGISTICS

A supply chain is a network of companies that convert basic resources (upstream) into final products (downstream) that are offered to the customers (Harrison & van Hoek, 2008, p. 7). The purpose of managing supply chains is to integrate the processes of all the supply chain parts as much as possible. The end customer is the most important one, as it is the part which starts the entire process with buying finished products. This behaviour causes the material flow throughout the supply chain (Gattorna, 1998). The concept of supply chain suggests that different processes are linked together to form a supply chain as shown in Figure 10 (Harrison & van Hoek, 2008, pp. 8-9). In every supply chain, logistics has in important role in each part of the chain. It is involved with the supply, storage and movement of materials, personnel, equipment and finished goods within a company and between a company and its environment (Ghobadian, Stainer, Liu, & Kiss, 2016, p. 103). Its goal is to get the right materials to the right place at the right time, while optimizing the performance within a set of constraints (Ghiani, Laporte, & Musmanno, 2004, p. 1). As represented in the Figure 10, each link can connect with several others that can extend to multiple organizations.

Figure 10. Supply Chain Network



Source: Slack et al., *Operations Management*, 1997, Fig 1.2.

Materials come as inputs from the left side, upstream side or »demand side«, to the right downstream or »supply side«. Every supply chain is an interconnected system, where organizations inputs and outputs are affected by other organizations involved in the supply chain (Harrison & van Hoek, 2008, pp. 9-18). The shape of a supply chain can be affected by distribution channels, which are a path that product follows to the end user. While some

manufacturing companies can sell directly to their end users, there are usually intermediaries between the manufacturer and the end customer. Intermediaries add mark-up to the products cost, which increases the final price to the end customer (Ghiani et al., 2004, p. 10).

3.1 Space Sector Supply Chain

Extremely high costs, budget tightening, and large investment needs required in the space industry bring the supply chain management (hereinafter: SCM) forth, as the enabler of the space industry future development. Due to investments of such a large magnitude, there is a need for engineering community to be aware of importance of the SCM, as it will have an important economic role. The space industry will need to apply supply chain practices of high-volume commercial industry to its low-volume, schedule driven environment. This would be very important for accurate estimations, planning, controlling and managing the non-recurring and recurring costs (Galluzzi, Zapata, & Steele, 2006, p. 1).

3.1.1 Supply Chain Structure

From the perspective of economics, an industry is typically subdivided into major suppliers and lower-tier companies down the supply chain. Components are provided from the lower-tier suppliers up the chain to a higher tier, where they are integrated into larger units. The last one is the top-tier provider, which provides the full system or service to the customer. This type of organization can also be applied to aerospace industry (Hayward, 1994, p. 6). While there are some "pure" space companies, many products are provided by very large companies with highly diversified product lines. These are mostly companies providing aviation, defence and space products to governments and other companies. The largest ones are Boeing in the USA, and Airbus group in Europe. They are both best known for producing commercial airline aircraft, but also manufacture many products for defence and space sector (Johnson, 2007, p. 155).

Top-tier suppliers who supply entire launch vehicles, satellites, aircrafts and missiles are also known as the prime contractors or integrators. Massive prime contractors were created with engagement in horizontal and vertical consolidation. These mergers would not be possible if the governments did not approve them, or at least declined to intervene in preventing them (European Aeronautic Defence and Space Company, 2003, pp. 70-71). Many of the mergers occurred in the late 1940's through the 1960's and again in 1990's and early 2000's. Although many of them have some sub-system design capabilities, most of the components are outsourced (Near Earth LLC, 2009, p. 20). Below the giant prime contractors, there are second tier companies. The latter are still very large companies, often with significant interest outside of the aerospace. Some examples are International Business Machines (IBM) involved in information technologies, or Pratt & Whitney, the builder of jet and rocket engines. Some of the second-tier suppliers also build full systems as well as components, and are usually considered as second tier suppliers because they are much smaller than the giant first-tier

companies. The last tier is occupied by component suppliers, which are below subsystem suppliers. There are hundreds of component suppliers which specialize in a small set of products, such as sun sensors, batteries or actuators to mention a few (Johnson, 2007, pp. 156-157). The market opportunity for the second and the third tier suppliers is only a fraction of the total manufacturing market. Since prime contractors tend to outsource much of the sub-system development, it most likely represents a majority of total economic input to the industry (Near Earth LLC, 2009, pp. 20-21).

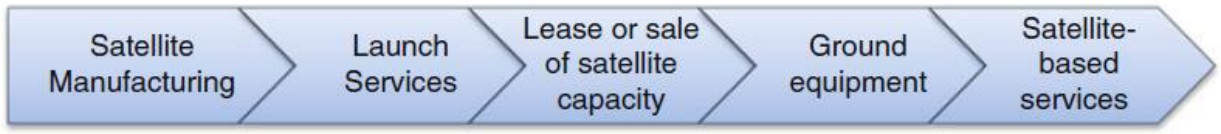
All the launch providers are potential suppliers to spacecraft operators. Operators will compare them and ask for bids to launch. Launch providers must be aware of that, and should set their prices and services partly based on benchmarking. Although all suppliers are potential competitors for all the launches in theory, that is not exactly the case in practice. Some launches, such as the US military or intelligence satellites, can only be launched by the US suppliers. Similar restrictions apply to other countries. We can consider space transportation as a single sector, but in practice it also consists of several partly independent sub-sectors. For example, small satellites can be launched by any launcher, but large satellites only by large launchers (Johnson, 2007, p. 160).

One factor that sets space industry apart from others is the very long lead times that apply to most space products and services. It takes a long time to bring the project from the idea phase to orbit. Delays are common. However, lead times remain long even if there are no delays. The main reason is the technical complexity of space projects. Furthermore, complicated facilities for testing and manufacturing must be built, space qualification tests themselves are very time consuming, as well as regulatory overhead (spectrum allocation, various clearances etc.) (Gortuna, 2013, p. 24).

3.1.2 Value Chain

Value chain represents all the parts that contribute to the final product or service that is offered to the customer. Compared to supply chain, which is mostly connected to getting the product to the final customers through multiple tiers, value chain adds value to the product with the activities, such as R&D, marketing and packaging (Comparing Value Chain and Supply Chain, 2016). Each part of the value chain adds some value to the final product or service. For example, let us look at satellite television broadcasting. The entire value chain should operate flawlessly to provide reliable and affordable service to the customer. A TV content provider who has leased satellite capacity from the satellite operator provides broadcast signals coming from the GEO. The operator must maintain satellites orbit and various subsystems to ensure it works optimally. Down the value chain, satellite operators are also dependent on their suppliers. Ground equipment manufacturers, satellite manufacturers and launch service providers are included, as illustrated in the Figure 11. These are supported by hundreds of other companies that provide hardware and software components (Gortuna, 2013, pp. 12-13)

Figure 11. Satellite Applications Value Chain



Source: Gortuna, *Fundamentals of Space Business and Economics*, 2013, Fig. 2.2.

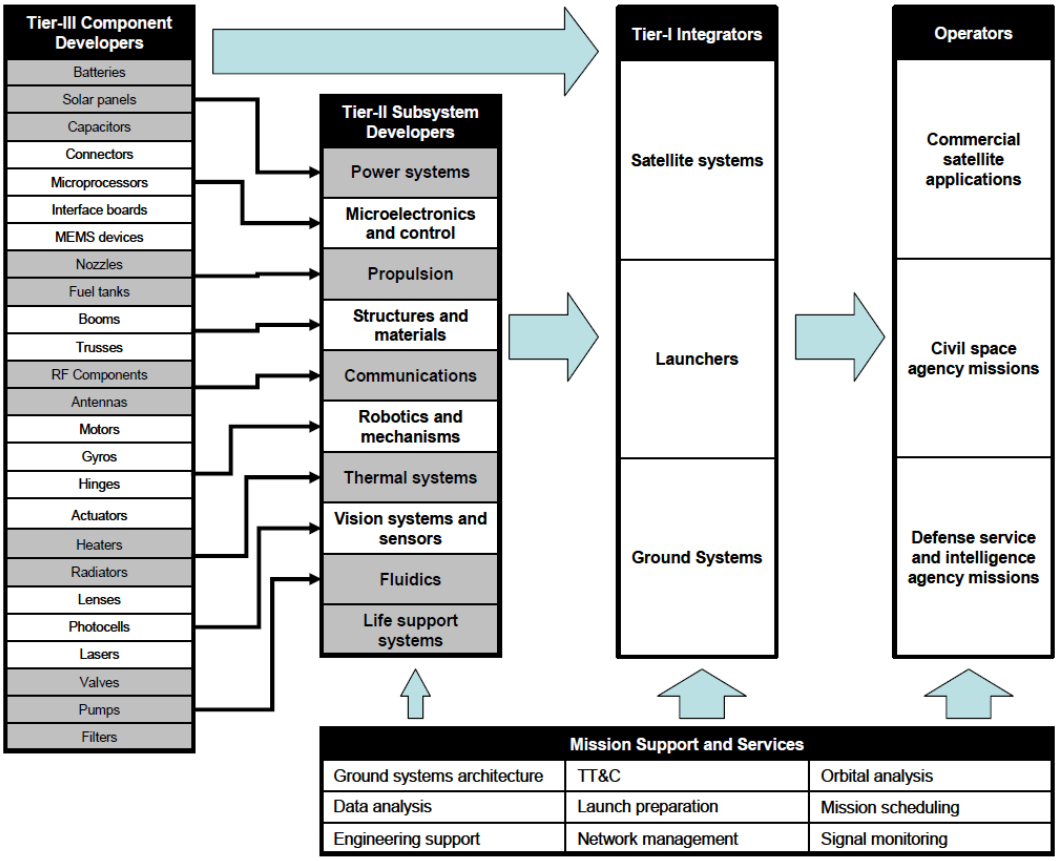
The end user market support for civilian, military and commercial customer segments is provided by the two very important secondary commercial space markets (Near Earth LLC, 2009, p. 8):

- Satellite manufacturing and launch providers, and
- The ground segment.

The first one builds and places satellite systems into orbit and the second one is comprised of companies that design and manufacture satellite communications equipment, produce software for satellite communications or operation, integrate or operate satellite communications or control facilities, and provide a wide range of engineering and other services for operations support (Near Earth LLC, 2009, p. 8).

Due to many vertical integrations and thus lack of competition in the industry, the prices of components increased. Not only that the prices increased, this also presented a problem with quality control variability and availability problems, which lead to companies such as SpaceX to develop their technology in-house (Hertzfeld et al., 2005, p. 27). Space sector value chain is presented in Figure 12.

Figure 12. Space Activities Value Chain



Source: Near Earth LLC, *Small Aerospace Companies Space Activities in North America and Europe*, 2009, p. 22.

3.2 Space Logistics

The term space logistics is basically application of logistics techniques to space systems. It is a process of planning, analysis and execution of maintaining and supplying space systems after they launch (Evans, n.d.). Similar definition by AIAA Space Logistics Technical Committee states that space logistics is the science of planning and executing movement of material and humans to, from and within space (Snead, 2004, p. 5). The goal is to maximize mission potential considering vehicle performance and infrastructure capabilities. It tries to tackle the two key questions (Armar, 2009, p. 17):

- How to optimally ship cargo and supplies with a given mission architecture?
- What cargo and supplies should be shipped depending on each individual mission?

In terms of infrastructure and processes, space logistics can be divided in 4 segments. In each of them, logistics planning and product support take different shapes (Breidenbach, 2011, p. 28):

- Space segment,
- Control segment
- Terminal segment, and
- Launch segment.

The space segment includes satellites that were already launched and only have contact through sending commands and receiving telemetry data. During the development of space segment, logistics activities focus on reliability, mission capability and reduction of downtime (Breidenbach, 2011, p. 28).

The control segment is made of computer workstations, equipment for satellite command codes formatting and satellite telemetry data translation, and a worldwide network of tracking stations for satellite communication purposes. During development, logistics activities focus on reliability, security and maintainability, as well as minimization of lifecycle costs (Breidenbach, 2011, p. 28).

The terminal or user segment consists of various equipment for satellite payloads. This includes radio frequency equipment for receiving signals from the payload, transmitters, and processing and display equipment. Logistics activities during the development focus on maintainability, reliability, and supportability applied to communications and electronics. They are more oriented on maintenance and repair in comparison with space and control segments (Breidenbach, 2011, pp. 28-29).

The launch segment includes the space launch vehicle. These are very complex systems that must be very reliable during their short operational cycle. Consequently, the focus of logistics activities during the development is on high reliability, redundancy and safety (Breidenbach, 2011, p. 29).

For various mission types, there are several logistics methodologies that can be used depending on the type of the mission. Classification of different logistics methodologies is based on the study of terrestrial supply chains (Armar, 2009, p. 19):

- **Pre-positioning –** this methodology focuses on sending cargo and required supplies to the destination ahead of the crew. This is usually executed with unmanned vehicles in the early mission phases. Vehicles deliver cargo and supplies in bulk. This can also be achieved by using excess cargo capacity on manned flights, to gradually build up supplies.

- **Carry-along –** with this approach, all the cargo is brought along on the mission. Each mission is self-sustained and its duration, performance and scope are limited by the cargo space available on the vehicle that is used.

- **Resupply –** on resupply missions, a certain amount of cargo is carried on board. Further in the mission, it is supplemented by scheduled and/or need-based resupply flights. Scheduled flights are planned according to predicted demand. Need-based resupply flights might be difficult to achieve due to long lead times required for launch preparation and final execution (depending on the location).

- **Depot –** this approach involves the use of a distribution centre, between the origin and destination of the cargo. This methodology is similar to terrestrial supply chains where inventory is stored in a depot until it is demanded by the customers.

Some examples of space logistics systems providing the defined logistics function (Snead, 2004, pp. 9-10) are:

- RLV's for routine transportation to and from LEO.
- Space logistics bases in LEO from which logistics services are undertaken.
- Modular space logistics vehicles for passenger and cargo transportation in space, which also provide maintenance support for satellites and other space platforms.

3.3 Reverse Logistics

Reverse logistics deals with the flow of products that go back up the supply chain due to repairs, product returns, maintenance and life cycle end returns, for recycling and dismantling. It includes both service (repairs, recalls etc.), and environmental component (Harrison & van Hoek, 2008, p. 129). Table 3 shows some differences between forward and reverse logistics.

Table 3. Forward and Reverse Logistics Comparison

Forward logistics	**Reverse logistics**
Relatively straightforward forecasting	More difficult forecasting
Many distribution points	Many to one distribution points
Uniform product quality	Product quality not uniform
Uniform product packaging	Product packaging often damaged
Destination/routing clear	Destination/routing not clear

table continues

continued

Forward logistics	**Reverse logistics**
Relatively uniform pricing	Pricing is dependent on many factors
Importance of speed recognized	Speed is often not considered a priority
Forward distribution costs easily visible	Reverse costs less directly visible
Consistent inventory management	Inventory management not consistent
Manageable product life cycle	More complex product lifecycle issues
Straightforward negotiations between parties	Negotiations complicated by several factors
Well known marketing methods	Marketing complicated by several factors
Transparent process visibility	Less transparent process visibility

There are several reasons why reverse logistics is often only partially incorporated into network design. A few are mentioned below (Harrison & van Hoek, 2008, p. 129):

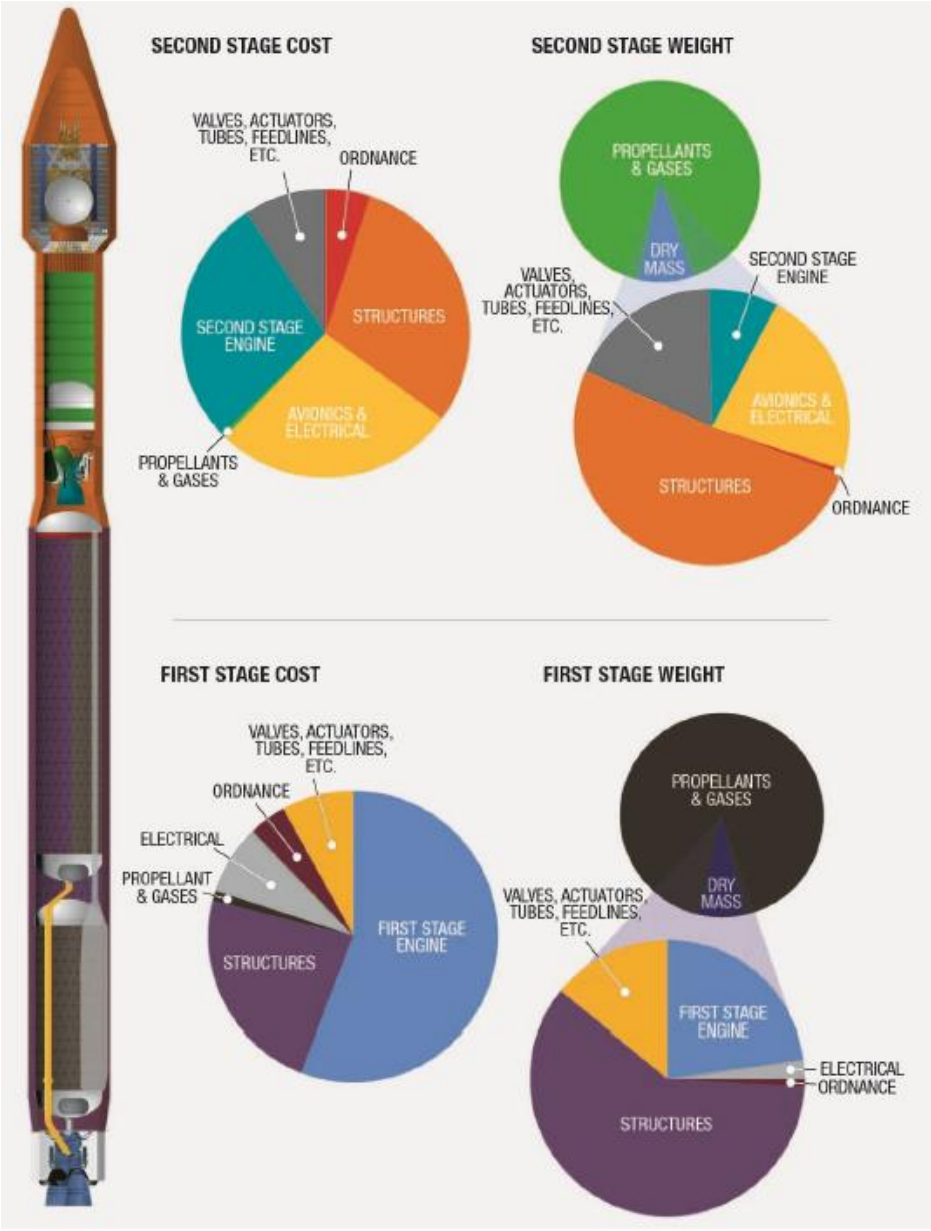
- Lack of infrastructure
- Not a top priority and does not receive sufficient resources
- It is not yet driven by business value but mostly by legislation
- Reverse flow and composition are hard to forecast.

Reverse supply chain is constructed out of series of activities that are required to retrieve used products for recovery, or to ensure a proper disposal of the product (Pochampally & Gupta, 2004; Ravi, Shankar, & Tripathi, 2011; Krikke, Hofenk, & Wang, 2013). The condition of the collected used products is very important for remanufacturing production facilities (Gu & Tagaras, 2014, p. 1). In connection with the emerging internet of things, real-time monitoring of supply chain can be achieved: from design, purchasing, production, transportation, to sales as well as returns (Atzori, Iera, & Morabito, 2010).

Reverse logistics will play an important factor with development of RLV's as well. With reusability, costs are planned to decrease, as well as the use of fewer resources (Bhavana, Mani & Prarthana, 2013, p. 1). Currently, reverse logistics is mostly applied to cargo, by ISS resupply services. The station must be regularly stocked, as well as cleaned. Waste, damaged and broken tools must be sent back down to the Earth for recycling (Evans, De Weck, Laufer, & Shull, 2006, p. 18). When it comes to launchers, there is some return logistics involved when parachuting the launcher back to the sea. After that, it is retrieved to land. However, it cannot be used again. When deciding which parts of the vehicle to reuse, it is important to

understand the relative value of each component. It is obvious that the most valuable component is the first stage, specifically the first stage engine. The cost of recovery plays an important part as there are different degrees of difficulty when it comes to retrieving a part of the vehicle (Ragab, Cheatwood, Hughes, & Lowry, n. d., pp. 3-4). In the Figure 13, stage ratio of cost and weight for Atlas 401 launcher is represented.

Figure 13: Launch Vehicle Cost and Weight by Major Element



Source: Ragab et al., *Launch Vehicle Recovery and Reuse*, n.d., Figure 5.

It can clearly be seen that first stage engine plays a great importance when it comes to costs, followed by different structural components. There are different recovery methods. However, retro-propulsion is probably the most intuitive. It is basically a reversed launch process. These technologies are still being tested and further developed, and it will be clear in the upcoming

years, if they present a major advance (Ragab et al., n. d., pp. 3-4). If RLV or partly reusable vehicles advance and become broadly used reverse logistics will have a major effect on cost reduction and efficiency.

4 OPERATIONS AND LAUNCH VEHICLES

4.1 Basic Operations

A spacecraft achieves orbit with initial boost from the rocket, which must be powerful enough to overcome Earth's gravity. For orbiting the Earth, rocket needs to speed the spacecraft at about 30,000 km/h. Once in orbit, the spacecraft keeps orbiting the Earth at a steady rate. Modern spacecraft have rocket thrusters that help with orbit adjustment from time to time (Jet Propulsion Laboratory, 2015, pp. 67-68). For the spacecraft to escape Earth's orbit, velocity must be much higher (Jet Propulsion Laboratory, 2015, p. 69). The hardest part of launching a spacecraft is still the first 100 km, which is also the biggest challenge the private industry will have to overcome. It takes 1,000 times more kinetic energy to launch a spacecraft to orbit than to fly a commercial jetliner (Morring, 2013).

Spacecraft is launched into different orbits depending on the mission purpose. The object needs to be positioned in correct orbits at correct altitudes. Some objects hover over a single spot, providing a constant view of a single area, while others circle the planet. There are three main types of orbits (Riebeek, 2009):

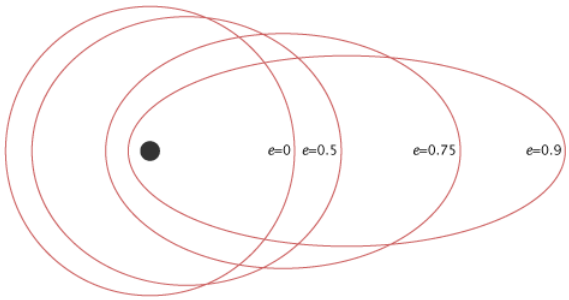
- Low Earth orbit (180 km – 2.000 km)
- Medium Earth orbit (2.000 km – 35.780 km) and
- High Earth orbit (> 35.780 km).

High Earth orbit is farthest away from the surface and usually occupied by many weather satellites and some communication satellites. Medium Earth orbit is in between, and reserved for navigation satellites and specialty satellites designed to monitor a particular region. Most scientific and Earth observation satellites are in the LEO (Riebeek, 2009).

How quickly an object moves around the Earth is determined by its altitude (distance from the surface of the planet). Object motion is mostly determined by gravity and as it gets closer to the Earth it moves quicker due to stronger gravitational pull. As an example, satellite that is about 705 km above ground requires 99 minutes to orbit the Earth, while one that is 36,000 km from the surface requires 23 hours, 56 minutes and 4 seconds to orbit the Earth. For comparison, the Moon, our natural satellite takes 28 days to complete a single orbit at the distance of 384,403 km from the centre of the Earth. Due to the fact that changing satellite’s height also changes its speed, an increase in the speed, using thrusters to accelerate the satellite, would cause it to go into higher orbit and consequently the speed would be decreased. So, the operator must fire the thrusters opposite to satellites forward motion, which

would put the satellite into lower orbit and increase its speed. There are also other variables that change the path of the satellite beside orbit height. These factors are eccentricity and inclination. Eccentricity determines the shape of the orbit. A satellite with low eccentricity orbit moves in an almost circular orbit around the Earth, while highly eccentric orbit is elliptical (in this case the satellite's distance changes depending on where on orbit it is (Riebeek, 2009). Eccentricity is illustrated in the Figure 14.

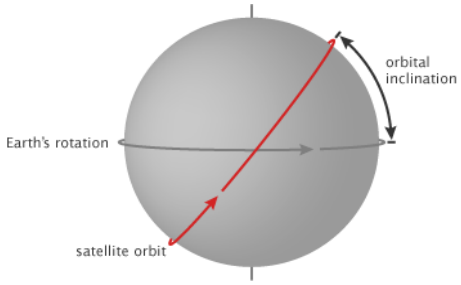
Figure 14. Eccentricity of Orbit indicating deviation from a Perfect circle



Source: Riebeek, *Catalogue of Earth Satellite Orbits*, 2009.

Inclination is a property which depends on orbit's angle in relation to Earth's equator. A satellite that orbits directly above the equator has zero inclination. If its orbit inclination is 90 degrees, it orbits from the North Pole to the South Pole (geographic, not magnetic) (Riebeek, 2009). Inclination is presented in the Figure 15.

Figure 15. Orbital Inclination Presenting an Angle Between the Plane of an Orbit and the Equator



Source: Riebeek, *Catalogue of Earth Satellite Orbits*, 2009.

Satellite's eccentricity, height and inclination together determine satellite's path and its view on the Earth (Riebeek, 2009). In the next section, we are going to take a closer look at different orbits and see what each of them is most suitable for.

4.2 Orbit Types

There are many different orbits we can launch a spacecraft to. Depending on the mission purpose, the following orbits are used:

- Geosynchronous Orbits (GEO) – It is a circular, low inclination orbit which takes an object 23 hours, 56 minutes and 4 seconds to complete. A spacecraft in this orbit appears to remain at the same longitude above the ground, although it may seem to move in the direction of north and south (Jet Propulsion Laboratory, 2015, p. 81).
- Geostationary Orbits – This is a geosynchronous orbit with a zero inclination, right at the equator or low enough so it can hang motionless above one point on the Earth (Jet Propulsion Laboratory, 2015, p. 81). It is very useful for weather monitoring and communications as it can provide a constant view of certain area (Riebeek, 2009).
- Geosynchronous Transfer Orbit (GTO) – To attain the above-mentioned orbits, a spacecraft first needs to achieve elliptical orbit at approximately 37,000 km. This is called Geosynchronous Transfer Orbit. The spacecraft then circularizes the orbit with its thrusters (Jet Propulsion Laboratory, 2015, p. 81).
- Polar Orbits – These are 90-degree inclination orbits useful for mapping and surveillance operations. Many of the Earth observing satellites have a nearly polar orbit. In this orbit satellite takes around 99 minutes to complete an orbit from pole to pole. During one half of the orbit the satellite observes the daytime side of the Earth and at the pole it crosses to the night side. By the time the satellite crosses back into daylight, it is over the region adjacent to the area it was observing in its last orbit. A satellite in polar orbit will view most of the Earth twice in a 24-hour period (Riebeek, 2009).
- Sun – Synchronous Orbit – Similar to geosynchronous satellites spot that lets them stay over one spot on the Earth over the equator, polar orbiting satellites also have a spot that lets them stay in one time (Sun – synchronous orbit). This means that whenever and wherever the satellite crosses the equator, the local solar time on the ground will be the same (Riebeek, 2009).

As air traffic is very dense in some areas, and there are many objects orbiting the Earth, every launch and orbiting object must be approved and monitored. This is regulated by the United Nations Office for Outer Space Affairs, space agencies, and national air traffic controls.

4.3 Space Launch Vehicles

Today, we still have not come to the point of mastering LEO. The cost of launching to orbit is still too high, and LEO frontier cannot be considered opened, until it is accessible for private individuals and companies at affordable prices (Heinlein paradigm) (Autino & Collins, 2010, p. 7). For now, the only way to launch a spacecraft from the Earth is with solid or liquid chemical propellant combustion. Many launches include the use of both at different stages of launch. Solid is usually less complex than liquid. However, from the ignition phase on, it

cannot be shut down. On the contrary, liquid and hybrid rockets can be shut down and reignited once again (Jet Propulsion Laboratory, 2015, p. 218). There are also other means of propulsion such as solar-thermal rockets, thermoelectric rockets, nuclear-thermal rockets and electrodynamic rockets, which are used in the space part of launch and will not be a part of this research (Federal Aviation Administration, n.d., pp. 25-28).

There are several factors one must consider when designing a space launch vehicle. The end purpose is to transport maximum payload amount with minimum costs safely to its destination, and consider the environmental impact (Stengel, 2008, p.1). Reliability is also a great factor when it comes to space launch vehicles. According to Saleh (2007), reliability is "the probability that an item (component, subsystem, system) will perform a required function under stated conditions for a stated period of time". Launch vehicle reliability is the probability that a mission will be completed successfully. It can be increased with different design options by adding redundant subsystems. Number of engines can be reduced, engine out capability can be added, and operating time can be decreased (Krevor & Wilhite, 2007, p. 2). Location of rocket launch is also an important factor of the launch process, not only because of the country's territory it is launched from, but also because of physics and cost factors. If a vehicle is launched near Earth's equator, it already moves at approximately 1,650 km/h relative to the Earth's centre. This means, it can take optimal advantage of the Earth's substantial rotational speed. It uses less propellant, or it can carry a larger spacecraft. However, if a vehicle is designated for a high inclination orbit, it does not affect it much (Jet Propulsion Laboratory, 2015, pp. 221-222). The chosen locations are also connected to safety, for diversion of vehicles into the ocean or desert in case of malfunction, and not on or near a populated area (Williams, 2011, p. 37).

4.3.1 Space Launch Vehicle Types

In general, space launch vehicles can be divided into expendable and reusable. With ELVs, a new vehicle is used for each launch. It lowers the cost per vehicle, structural ratio, assures continued production, and upgrades in production can be achieved easier. On the other hand, RLVs return to launch site after each use, where they are refurbished. They require high initial costs, high structural ratio, and some of the non-reusable parts require replacement with each launch (Stengel, 2008, p.1). However, RLVs might have cost advantages over time. Reusability topic will be discussed more in the chapter 6 of this thesis.

One of very important factors in the development of launch systems is "payload penalty". This is the amount of payload performance reduction in terms of mass-to-orbit because of additional dry mass (different parts, structure etc.) added to the vehicle. Payload penalty is the stage mass increase, which effects payload mass reduction. This also affects the business part, as the customers would like to pay as little as possible for every pound sent to orbit. Service provider must increase the price per kilogram sent to orbit to maintain the profit margin. That

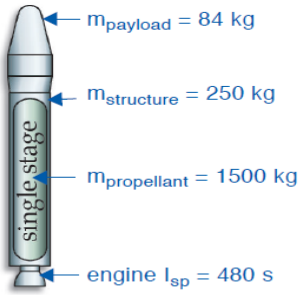
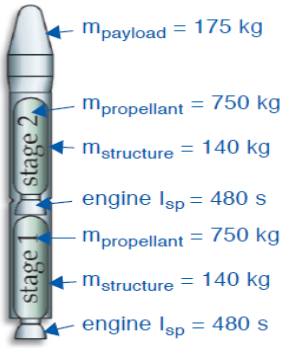
is why there is a lot of pressure to minimize the payload penalty when creating a new launch system (Kaplan, 2002, p. 1184).

Launch vehicles can be classified depending on their payload launch capabilities. There are four main classes of launch vehicles. Launch propulsion technologies are custom made to satisfy the needs of payload requirements. Small launch vehicles category can transport up to 2 tonnes of payload to the LEO, while medium size launch vehicles can take up to 20 tonnes. The upper range includes heavy launch vehicles that range from 20 to 50 tonnes and super heavy dedicated for payloads which exceed 50 tonnes (McConnaughey, Femminineo, Koelfgen, Lepsch, Ryan, & Taylor, 2010, p. 11).

4.3.2 Number of Stages

Hard reality of the rocket equation pushes designers to create launch vehicles that consist mostly of propellant. More than 80 per cent of a typical launch vehicle's lift off mass is propellant. About 5 per cent or less is accounted to payload and the other 15 per cent to structure, tanks, plumbing and other subsystems (Federal Aviation Administration, n.d., p. 43). The goal of many companies in the industry is to create a single stage to orbit (hereinafter: SSTO) vehicle, which takes off, goes to space and lands in one piece like every aircraft that has ever been built. To launch a SSTO vehicle, enormous engines and large amount of fuel are required, which add a lot of additional mass to the vehicle, and consequently requires larger engines and more fuel. If weight is increased on any part of the vehicle without an increase in performance elsewhere, there will be an equal decrease in payload capacity. For these kinds of vehicles, the payload penalty is one to one (Kaplan, 2002, p. 1184). However, there is a different story when it comes to spacecraft and launch vehicles in use today. Rockets shed stages as they go, because each component they lose decreases the mass of the vehicle and therefore makes it faster (Kluger, 2015). In case the vehicle has multiple stages, payload performance is not as sensitive to weight increases as the lower stages are separated when all the propellant is burnt. The payload penalty of the upper stage is always one to one, but lower stages have less of an impact. As an example, for two stage vehicles, the payload penalty of the second stage would be one to one, and for first stage it would be 10 to 1. From this it can be assumed that lower stage should be simple and inexpensive, while the second stage should be more complex and expensive. In other words, heavy (cheaper) material can be justified more on the first stage than the second (Kaplan, 2002, p. 1184). Comparison of a single and two staged vehicles can be seen in the Figure 16.

Figure 16. Comparison of Single-stage and Two-stage Launch Vehicles

Launch Vehicle	Parameters	Payload to Orbit
Single Stage 	ΔV_{design} = 8000 m/s I_{sp} = 480 s $m_{structure}$ = 250 kg $m_{propellant}$ = 1500 kg	$m_{payload}$ = 84 kg
Two Stage 	ΔV_{design} = 8000 m/s **Stage 2** I_{sp} = 480 s $m_{structure}$ = 140 kg $m_{propellant}$ = 750 kg **Stage 1** I_{sp} = 480 s $m_{structure}$ = 140 kg $m_{propellant}$ = 750 kg	$m_{payload}$ = 175 kg

Source: Federal Aviation Administration, *Rockets and Launch Vehicles,* n.d., Table 4.2.1-11.

The Figure 16 shows that more of payload can be transported to orbit with the use of multiple stage launch vehicles. A two-stage vehicle can carry more than twice the payload compared to a similar size single-stage vehicle with the same amount of propellant. This includes 10 per cent addition to structure's overall mass, to account for extra engines and plumbing required for staging. Therefore, all launch vehicles nowadays depend on staging. Another very interesting fact when it comes to staging is the law of diminishing returns. As the second stage significantly improves the launch vehicle's performance, each added stage enhances it less. By the time thhe fourth or the fifth stage is added, increased complexity and reduced reliability offset the small gain in performance. That is why most vehicles have only up to four stages (Federal Aviation Administration, n.d., pp. 43- 45).

Usually when rockets shed stages, they are expendable and fall into the ocean. However, there are companies that have managed to land the first stage back on ground to be refurbished, which might reduce costs dramatically. The first companies to achieve this were SpaceX and Blue Origin. Blue Origin landed a launcher flying to 100 km altitude, and SpaceX achieved it while delivering payload to orbit. SpaceX achieved an additional milestone when it landed the first stage at sea on a drone ship, which requires additional level of complexity and accuracy (Kluger, 2015).

4.3.3 Space Transportation Vehicle Parts

Usually launch vehicles also include different adapters that attach the spacecraft to the launcher. However, upper stages are commonly designed to fit a particular launch vehicle (Fox, Brancato, & Alkire, 2008, p. 29). A launch vehicle requires most of the same subsystems as the spacecraft. The biggest differences are operational time and total velocity change required (Federal Aviation Administration, n.d., p. 38).

Propulsion is the first subsystem. It presents several challenges such as thrust-to-weight ratio, throttling, thrust vector control, and nozzle design. To get the vehicle off the ground, thrust-to-weight ratio needs to be above 1.0, which means that produced thrust must be greater than the weight of a vehicle. Throttling (propellant flow management) and thrust vector control (manipulating the direction of thrust from the engine) are often required for a launch vehicle which makes it much more complex and expensive. Thrust vector control is used to control the altitude and angular velocity of the vehicle, and throttling to increase or decrease the engine power with regulation of propellant amount. For the most part, it is used at the early stages of the launch where atmosphere is still denser. If the thrust is constant, the acceleration will increase as vehicle gets lighter due to burnt propellant (Federal Aviation Administration, n.d., pp. 39-40). Solid propellant launch vehicles cannot regulate the amount of propellant used compared to liquid propellant launch vehicles. Their thrust cannot be controlled, and once ignited the engine cannot be stopped or restarted. However, they are relatively safe, simple and low cost. On the other hand, liquid propellant launch vehicles are the most powerful and adjustable. Due to their complexity, there is higher probability of malfunction and the costs are higher (Davis, Sher, Tian, & Vasileva, 2012, pp. 4-5)

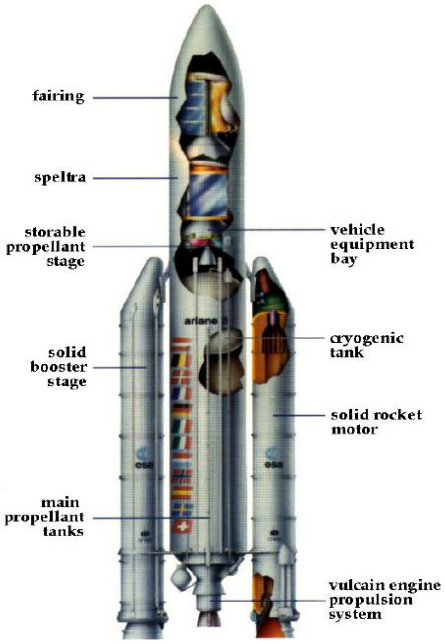
Navigation, Guidance and Control is the second subsystem, which keeps the launch vehicle aligned along the thrust vector, to prevent dangerous side loads and ensures the vehicle reach the intended position and velocity for the planned orbit. It includes various sensors such as accelerometers and gyroscopes for acceleration and altitude change measurements. Newer systems rely on GPS for additional position, velocity, and altitude information (Federal Aviation Administration, n.d., p. 41).

Communication and Data Handling subsystem provides contact with the vehicle throughout the launch. Telemetry from launch vehicle subsystems is constantly being monitored by flight controllers. Communication and data handling subsystem is therefore required on board, to deliver telemetry to the control centre. For ELVs, these can be very simple as they are only required to work for a few minutes. However, they still need to be very robust due to vibrations and acoustic environment. Launch vehicles trajectory is monitored by a separate tracking radar, with self-destruct command in case the vehicle drifts from its planned flight path, and endangers people or property (Federal Aviation Administration, n.d., pp. 41-42).

Electrical Power subsystem in a launch vehicle is very modest compared to the one in a spacecraft. Most of the power required is used for communication and data handling subsystems, as well as sensors and actuators. ELVs typically rely on relatively simple batteries for primary power during launch due to their limited lifetime. However, Space Shuttle, for example, used fuel cells powered by hydrogen and oxygen (Federal Aviation Administration, n.d., p. 42).

Structure and Mechanisms is the last subsystem and is related to vehicles structure and mechanisms. Launch vehicle can have tens or even hundreds of thousands of individual nuts, bolts, panels, and load-bearing structures. Due to the fact that most systems contain propellant tanks, they tend to dominate the entire structural design. They often become a part of the primary load-bearing structure. In addition to problem of launch loads and vibrations, there are many individual mechanisms for separating stages and other mechanical processes throughout a mission (Federal Aviation Administration, n.d., p. 42). Launch vehicle designers should accurately and carefully integrate all the structures and mechanisms to design an integrated compact launch vehicle. In the Figure 17, Ariane V cut-away is presented. A large part of it is occupied by propellant tanks and engines. All the other subsystems are packed into the secondary structure. It can also be seen that each stage has its own engines (Federal Aviation Administration, n.d., pp. 42-43). The most important factors that drive the design process are financial limitations, mission goals, and physical constraints. Optimally, a vehicle should be as small and light as possible. This very much depends on payload, material quality and, of course, financial backing (Nassar, Bonifant, Diggs, Hess, Homb, McNair, Moore, Obrist, & Southward, 2004, p. 3).

Figure 17. Ariane V Cut-away



Source: Federal Aviation Administration, *Rockets and Launch Vehicles*, n.d., Figure 4.2.1-55.

5 SPACE TRANSPORTATION SYSTEM FINANCING AND CONTRACTING

5.1 Financing of Space Projects

While commercial ventures are required to make profit, governments are usually trying to maximize the cost-benefit ratio. Private space ventures usually employ expert scientists, but they have some degree of advisory from the government. Most of important innovation and research in the USA is publicly funded. This was the system that made the first computers, GPS, internet, laser scanners and other inventions possible. Science investments in companies looking to create revolutionary products have a very high return on investment (hereinafter: ROI) ranging from 20 – 40 per cent (Satell, 2016). Allowing a commercial company to piggyback a governmental project can bootstrap further space operations and offset some of the costs incurred by the government. Both outcomes are beneficial. However, there is a question of participating company's selection that might have political and economic consequences (Gertsch & Gertsch, 2015, p. 1). Limited funding and lack of investors interested in space projects are the obstacles that private companies have to face. Most private investors are driven away by the lack of economies of scale, very long development cycles, technical risk and strict governmental regulation. Moreover, it is also extremely hard to acquire conventional early stage financing, such as angel investors and venture capital (Gortuna, 2013, p. 46).

For commercial space launch industry to take-off, sources of revenue should be identified. Sales are generated by two complementary occurrences, product existence and market for the product. In the space industry, many products have been identified, but markets either depend solely on governments, or they have not yet been identified. Sometimes it is very difficult to calculate the true value of the product in this environment and profit equation can be meaningless. For assessments, the below tools are used most commonly (Gertsch & Gertsch, 2015, pp. 2-4):

- **Discounted Cash Flow (DCF)/Return on Investment (ROI)** analysis – This analysis projects cost and revenues for the proposed time period of a project. It also accounts for the value of money over time (the discount), and the required income as a percentage of the investment (the ROI).
- **Net Present Value (NPV)** analysis – It takes multiple revenues and costs over time in the DCF/ROI and calculates the present value of the entire project.

Payback periods also play a very important part. Most commercial projects have a payback period of 3 – 5 years, as shorter time periods limit the exposure to risk. If risk is higher, shorter payback period and higher ROI will be desired (Gertsch & Gertsch, 2015, p. 4).

5.2 Contracting

The primary source of revenues for aerospace companies is contract based work, awarded or negotiated with primary contractors (i.e. government agencies or commercial operators). There are two major methods from a compensation point of view (Near Earth LLC, 2009, p. 21):

- Cost plus – compensation is determined as a function of cost as well as a predetermined profit. Cost is determined with time and materials or agreed upon estimate (can also be a combination of both). The "plus" component can be either a flat rate or awarded in relation to performance metrics. These kinds of contracts are often awarded to technically demanding projects with too high resource uncertainty required to complete the task, to take on a fixed price contract. This allows many companies to take on very challenging, high risk projects. This method is commonly applied to many governmental contracts.
- Fixed price - Compensation is based on a flat price paid on deliverables. Commercial customers prefer this method as it protects them from cost overruns. A government uses this type of contracting when it is feasible.

Due to strong reliance on cost plus contracts in the space sector, distinction between costs and price is not always clear. The contractor is entitled to total project costs reimbursement in addition to the profit based on percentage of the cost base. Thus, the contractors do not have much of a reason to control the project costs. Communications satellite industry was one of the first to migrate from this model by demanding a fixed price bidding process (Gortuna, 2013, p. 12). Although price uncertainty is a great cost-plus contracts disadvantage, they are relatively efficient for managing highly complex projects with strategic importance. In times of war or intense international cooperation, a government can make the budgetary risk and make the overall risk acceptable for private sector contractors. However, when activities become more of a routine, fixed-price contracts are more efficient for minimizing costs and budget overruns (Gortuna, 2013, p. 71). The main differences are presented in the Table 4.

Table 4. Fixed Price vs. Cost Plus Fee

Model Input Assumptions	**Fixed Price**	**Cost Plus**
Acquisition Strategy	No Oversight	Oversight
Requirements Stability	Stable	Unstable
Management Structure	Lean	Less Lean
Early Phase Studies / System Engineering	Disciplined	Less Disciplined
Funding Commitment	Fixed	Annual

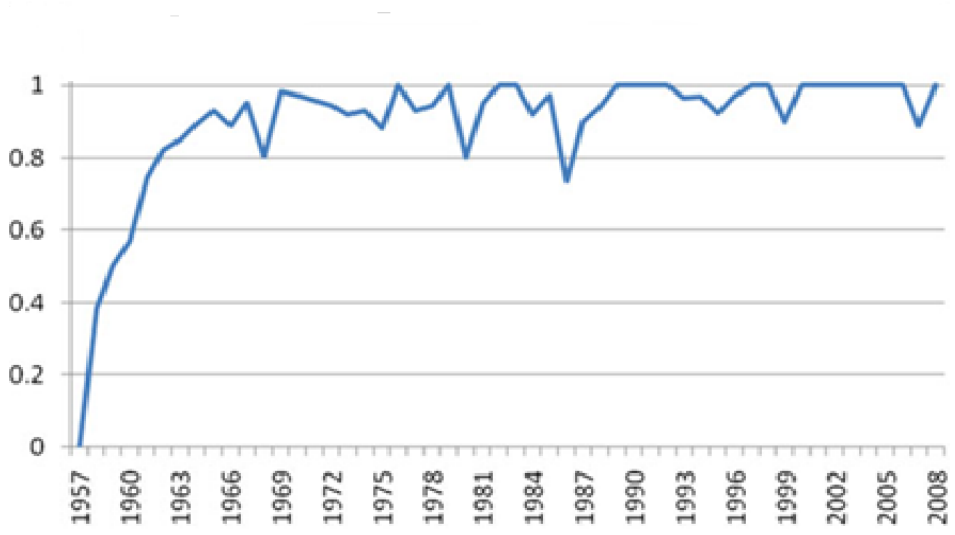
Source: National Aeronautics and Space Administration, *Falcon 9 Launch Vehicle NAFCOM Cost Estimates*, 2011, p. 6.

When companies or the government agree on certain contracts, there is still a lot of risk involved in the entire process, from manufacturing to launch and operations in space. I will briefly present how risk is managed in the space industry, and the types of risk connected to a space mission.

5.3 Risk Management

In general, risk is probability of a negative occurrence caused by internal or external vulnerabilities, and may be avoided through pre-emptive action (Risk, 2017). It can also be explained as intentional interaction with uncertainty (Kungwani, 2014, p. 83). Space environment is very harsh and very risky. There have been many lost unmanned missions throughout the years. However, failed manned missions are much more serious, causing great impact on the industry and the society. Compared to the historical track record of mission failures, there have been great advances in managing and containing risk. At the beginning of the space age, failure rates were at about 50 per cent. Nowadays, these rates decreased to approximately 5 – 10 per cent for robotic missions and even lower for manned missions (Gortuna, 2013, p. 56). In the Figure 18, ratio of successful missions compared to total number is represented. Low level of success can be seen in the early years, from 1957 to the late 1960s and early 1970s. There have been some decreases in the 1980s. Since 1990, however, it has remained relatively constant.

Figure 18. Ratio of Successful Mission to Total Number of Mission from 1957 till 2008



Source: Gortuna, *Fundamentals of Space Business and Economics*, 2013, Figure 7.1.

There are different types of risk connected to spaceflight (Gortuna, 2013, p. 57):

- Cost risk: Space programs usually do not have the best accuracy when it comes to cost estimation. Cost risk includes two main potential threats. These are inaccurate cost

estimates, and cost overruns due to requirement changes, technical problems or schedule slippages.

- Schedule risk: Inaccurate project duration estimates or schedule slippages can threaten the performance of the space project. In many cases, it results in cost overrun, and in some cases, it can be crucial for meeting a specific launch date due to limited launch windows.
- Technical risk: History of space launches is full of accidents, launch pad explosions and mission failures due to technical malfunctions of hardware and software.
- Programme risk: Sometimes regulations and laws can substantially affect the success of a space mission, which is beyond the control of the project manager and includes risks such as changes in policy imperatives.
- Market risk: This type of risk may not be much of a concern for space agencies. However, it can be a huge issue when it comes to the private sector. Even though a space project can progress according to schedule and within projected budget, any significant changes in demand can have devastating consequences for the business.

In addition to the above-mentioned risks, the fact is that human error can also cause devastating outcomes. A very good example is when Mars Climate Orbiter spacecraft disintegrated during orbit insertion around Mars in 1999. Investigation revealed that the cause for this event was in the on-board software. The Orbiter was designed to process thrust instructions using metric unit Newtons, while ground control executed the instructions using imperial measure pound-force. Thus, even though the hardware and software performed flawlessly, one single software code caused a loss of mission due to conversion of physical units (Gortuna, 2013, p. 58).

Keeping track of all the risks is a challenging task. Identifying and mapping risk is very useful for organization to understand the challenges and risks ahead. Total elimination of risk is unfortunately not possible, but calculated risk can be applied and is essential for missions as well as business. We can actively reduce it by mitigating it, or we can purchase insurance to offset the financial losses. These two actions are not mutually exclusive as we can invest a certain amount for risk mitigation, and transfer the rest of the risk through insurance products (Gortuna, 2013, pp. 58-61).

5.4 Insurance

In the early days of spaceflight, a government funded all the launches. If one of the launches failed, it funded a replacement, occasionally in advance. Another concern was liability. Citizens could not sue the government if a rocket fell on their property. Commercial companies were in a different situation. They could quickly go bankrupt if a commercial launch caused damage to someone's property. Furthermore, they could not afford to build two copies of a spacecraft to ensure it would work. The Outer Space treaty of 1967, and 1972 Convention on International Liability for damage, required that nations are required to pay for damage caused to other nations and motivated them to set minimum liability insurance

requirements on private organizations. When failures occur, insurance companies press the companies to fix the problems before they would insure another launcher or satellite (Johnson, 2007, pp. 186-187). The US government may pay the third-party liability claims for injury, damage or loss that resulted from commercial launch – related accident in excess of required "maximum probable loss", which is calculated by FAA and is limited to $500 million per launch, or amount available at reasonable cost (Federal Aviation Administration, 2015, pp. 15-16). Insurance can be classified in different phases of the spaceflight process. Firstly, there is a pre-launch insurance which covers damages or loss of satellite or launch vehicle during manufacturing, testing and transporting. Secondly, there is a launch insurance, which starts from the beginning of the launch phase. And lastly, there is an in-orbit insurance, which is mostly used for satellites and offers protection against the risk of satellite failure. Usually it is renewable on a yearly basis (Aon Risk Solutions, 2016, pp. 6-9).

6 SPACE TRANSPORTATION SYSTEM COSTS

Sending objects to orbit is still extremely expensive, estimated at around $5,000 to $15,000 per pound depending on the altitude or orbit of the payload destination. However, there are companies tackling this problem and the leading one is SpaceX. Quickly after the company's launch, SpaceX started producing rockets that are less expensive. A large factor contributing to the low price is manufacturing of most of the subcomponents in-house, thus eliminating subcontractors. To lower the costs even further, they believe reusable technology development is required. Ideally, a space vehicle would take off, land and then be ready to be used again in a short timeframe. This was already the vision for the Space Shuttle. However, the boosters that powered the Shuttle during the first two minutes of launch were parachuted into the ocean and recovered by NASA ships. Later, they were refurbished, but it took months to get them ready for another launch and the costs increased rapidly. One of the biggest limitations of new launch opportunities is still a low number of customers. Additionally, these customers place a lot of focus on reliability, as opposed to the cost (Nature, 2005, pp. 711-712). Heavy lift vehicles are used for transporting large payloads, usually security related or communication satellites to GTO. In this case, the customers value reliability and assured access to space much more than the price itself. For a private communications satellite, total cost of the satellite and launch present a fraction (10 - 20 per cent) of the revenues that are usually generated by the sale of services over 10 to 15-year life cycle of the satellite. That is why in many cases a few million dollars will not make a difference in launch vehicle demand, which is very inelastic especially with heavy launch vehicles (Hertzfeld et al., 2005, p. 25). For example, we can take the James Webb Space Telescope worth $4.5 billion. If the payload costs much more than the rocket itself, the client is prepared to pay extra for the payload to be transported safely to orbit. Compared to cost of failure, extra tens of millions of dollars in savings do not matter much (Nature, 2005, pp. 711-712).

On the other hand, there is more price sensitivity with smaller payload launches. These are often scientific, research or specialized services. Launch delay is often not as important to the

smaller payload client as it is to the heavy lift clients, and the cost of payloads is usually not as great as for the large satellites. Consequently, less up-front money is involved so the time-value of money assigned to risk of delay is lower. Furthermore, because it costs less to develop a smaller launch vehicle, there are more options available to the client which translates into greater competition in the market. Thus, the price elasticity is higher (Hertzfeld et al., 2005, p. 25).

6.1 Spaceflight Cost Overview

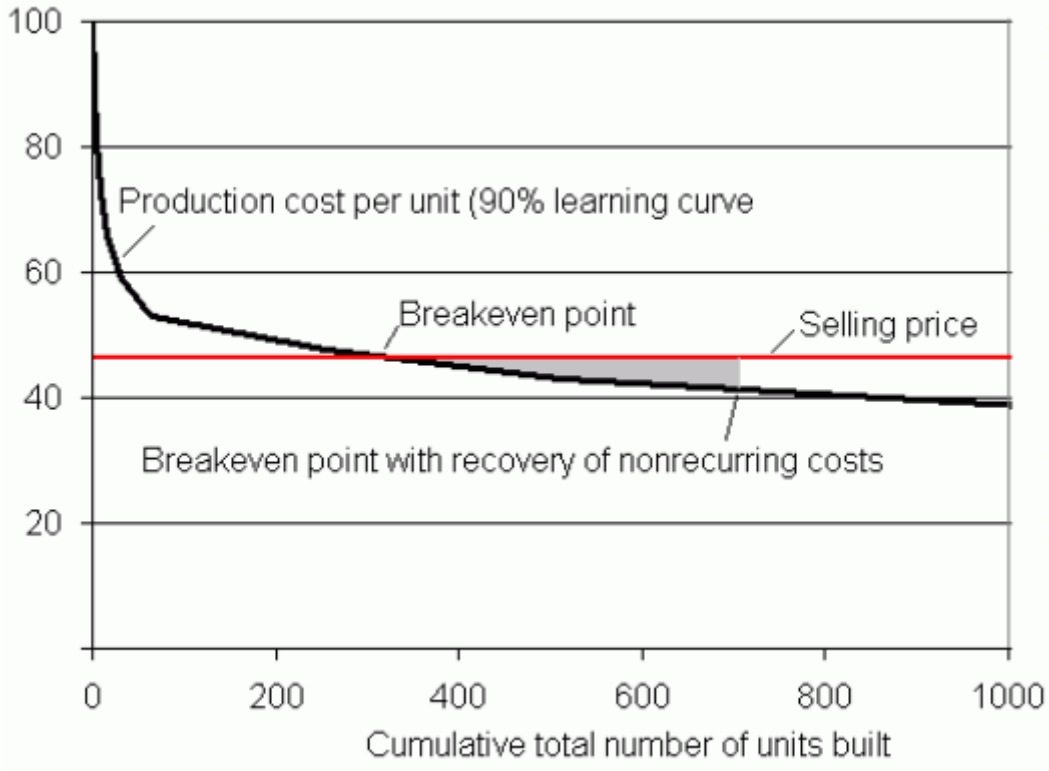
Most of the space projects are designed, built, and operated by finding the most optimal balance between performance, risk, cost and schedule. During the space race, cost and risk reduction was put on the side-track. Resources by the Soviet Union and the USA were poured into the space program for maximization of performance. Space industry is very much different nowadays, as agencies and private companies try to manage costs of space projects as efficiently as possible. High costs occur due to complexity of the projects, similar as in other sectors such as nuclear power plants, military projects, and large-scale infrastructure investments, which are all prone to significant cost overruns (Gortuna, 2013, p. 66).

The fundamental technology behind space launch vehicles has remained the same since the beginning of the space age (chemical propulsion and solid/liquid propellant). It would be natural that the costs would significantly decrease over decades through incremental improvements and economies of scale. Despite of many years of development and researching, this has not been the case (Gortuna, 2013, p. 45). Space programs have been known for their high costs and cost increase when moving from concept to orbital operations. Designing a vehicle which operates in space requires a design that can deal with high temperature variations, and high level of radiation exposure. Components are custom made for this purpose and need to be accurately integrated into the space system, as the cost of failure is very high. There is still a high degree of industry customization, even though there were standardization attempts to reduce non-recurring costs and simplify the production (Fox et al., 2008, p. 1).

One of the main issues in space system development is the distinction between recurring and non-recurring costs. Costs like R&D and ground infrastructure are non-recurring costs, and can be spread over multiple missions. On the other hand, there are recurring costs, which are mission specific and are incurred with each mission launch and operations. In most industries, non-recurring costs are spread over millions of units produced, minimizing the cost per unit of the product. On the contrary, as space manufacturing is a very low volume industry, costs per unit are extremely high (Gortuna, 2013, p. 66). Historically, the main design criterion in space programs was maximizing the performance, which was mistakenly seen as a synonym for weight minimization. This is not the case anymore as costs have become the new design criteria (Trivailo, Sippel, & Sekercioglu, 2012, p. 2).

As an example, we will take a look at commercial aircraft or launch vehicle producer on a competitive commercial market. When a company introduces a new model that will be cheaper to produce and operate compared to the previous models and competitors, it starts with high production costs per unit and lower production volumes. Eventually, it will cost less to produce and operate it, but initially it will be more expensive than competitors'. Even though a company invests billions of dollars in development and research and the first airliner may cost $350 million, they cannot expect to sell it unless the price is $140 million (Wade, 2013, p. 2). The company has to sell the units well below cost at first as shown in the Figure 19.

Figure 19: Production Cost and Selling Price of a New Aircraft Model



Source: Wade, *Cost, Price, and the Whole Darn Thing*, 2013, Graph 1.

Once the production rate grows, we come to the break-even point. After this point, the aircraft or the launcher is finally making money for the company. The difference between received funds for each vehicle and funds paid out to construct it is used to pay the non-recurring cost of the next generation of vehicles, interest or principle on loans, and offset the production cost of other newer model, where the production cost still exceeds the selling price (Wade, 2013, p. 2).

Almost all the studies in the past assumed that space transportation would become much less expensive in the next couple of decades. This conclusion was made under the assumption that larger space activity demand would result in spreading the costs over more flights. One of the

most common mistakes in the past was the extension of the historical trends into indefinite future. Historical launch analyses data have been accurately portrayed. However, there were two types of data extensions that were misleading decision makers (Hertzfeld et al., 2005, p. 6):

- The assumption "build it and they will come" on the demand side.
- Price for launch will decrease due to lower average costs with a demand surge, and radical new technological advances that will lower the costs.

Due to these assumptions, many past studies extended their predictions that average cost per kilogram to the LEO will decrease from approximately $20,000 to $200. This would influence the final price and stimulate new uses of space technologies. The problem with predictions like these lies with summary demand curves that include low cost access to space in the projections. It was thought that building cheap vehicles that can fly safely many times per year will decrease the price and increase the mass to orbit. In reality, private investments for future systems occur only when markets can be clearly identified. Furthermore, predictions often exclude launch weather conditions, technical glitches in complex systems, environmental risks, legal and regulatory obstacles. Compared to the mentioned obstacles, the largest is still the development of new technologies that provide high reliability at low cost. Many decisions for the future of space and vehicle development have been based on overly optimistic technological assessments rather than on the economic analysis (Hertzfeld et al., 2005, pp. 6-8).

To compare different launch systems, cost per pound or cost per kilogram metric is commonly used. A 2005 study concluded that oversupply in the launch vehicle market in the last two decades drove the price down, in some cases up to 50 per cent. Normally this would cause the demand to increase, but it remained stable. One of the reasons could be very long lead times for developing new payloads and building spacecrafts (Gortuna, 2013, p. 11).

Only with unit costs decrease, one can adopt a mass market of goods and services. If economies of scale are non-existent, unit production costs will most likely not decrease since one-time costs, such as R&D, engineering, design and commercialization costs have only a few ways to be divided. When an aircraft is designed by a company, they are basically creating an entire platform. Not only will they generate revenue from the sale of the aircraft, but also from multi-year servicing and training contracts. In majority, this is not applicable to current space industry (Gortuna, 2013, p. 25). One of the key cost drivers is building a single unit, customized to the client's needs. In aviation, automotive or industrial products manufacturing sectors, high quantity level production is the norm. The opposite is happening in the space industry, where design of the latest unit is processed, a few units are produced, flied once and then they move on to the next design (Gortuna, 2013, p. 46).

6.2 Cost Estimation Methods

Estimating exact space mission costs at the beginning of development is a very challenging task. Through time, with trial and error, three main methods have been developed: costing by analogy, parametric costing, and bottom-up costing (National Aeronautics and Space Administration, 2008, p. 24). These methods can be used together and as project progresses, we can move from one to another (Gortuna, 2013, p. 67).

Costing by Analogy starts with identification of past missions with similar project scope and complexity. Cost data from the past projects are used to evaluate cost estimates for the present projects. Depending on the project complexity, cost estimates may be significantly increased or decreased, which is based on required R&D effort intensity. This method is more suitable for repetitive projects with many examples from history and is relatively subjective. A good example is satellite telecommunication industry, where hundreds of historical cases can be used to draw data. Furthermore, as communication contracts are awarded on fixed-cost basis, analogy based estimates are very important to assess a bidder's quote. For many other projects, this method can provide misleading results and is not suitable. For example, if one took suborbital mission as a baseline for GTO mission, there could be great differences in performance requirements, life support systems, and mission duration (Gortuna, 2013, p. 68).

Bottom-Up Costing is commonly used in the construction industry, based on going through each specific task of a project and adding up all the cost elements that can be assigned to each task. By including additional expenses, such as materials and overhead, costs can be estimated very accurately. As project requirements change, cost estimates should be adjusted accordingly. A very high degree of precision is required when it comes to final design. Although this requirement can be met in terrestrial projects, this may not be possible in the early phases of project development for most space contracts. The client and contractor cooperate hand in hand to complete feasibility and design phases (Gortuna, 2013, p. 68).

Parametric Costing method relies on extensive mathematical analysis of historical cost data. It tries to identify cost drivers of a project at a detailed level (bottom-up approach is even more detailed). "Cost estimating relationships" are used to create the link between system cost and its variables. For example, if a sub-systems power requirement increases, costs would increase as well. An advantage of this method is to be able to perform "what if" analyses relatively quickly (Gortuna, 2013, p. 69).

6.3 Comparison of Reusable and Expendable Launch Vehicles

RLV concepts have been around for several decades. More serious reviews of potential designs began in the mid-1990s, when NASA suggested that replacement for the Space Shuttle had to be pursued. By the late 1990s it was clear that there will not be any operational RLVs anytime soon. Multiple factors contributed to this. The overly optimistic projections of

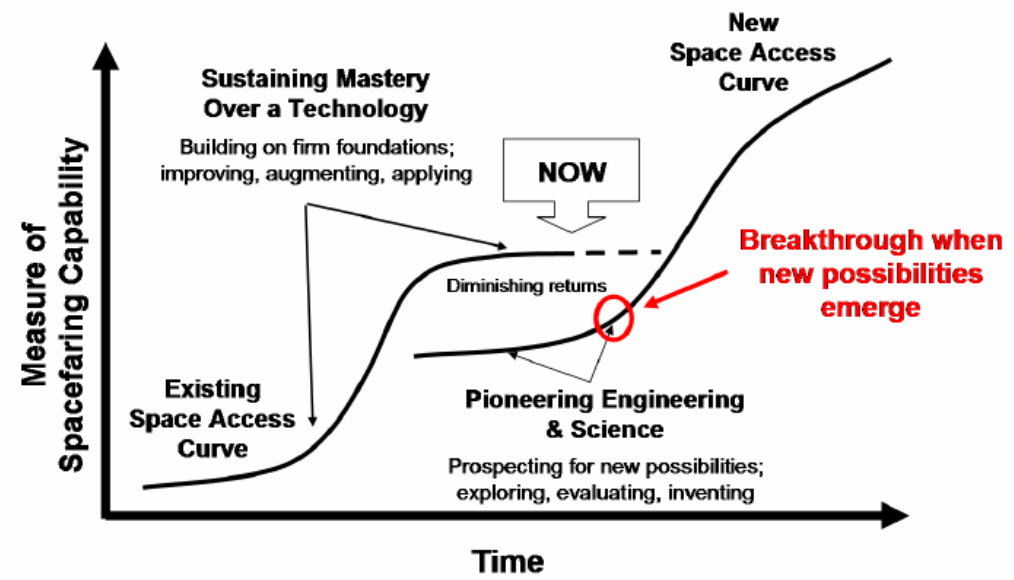
technological advances, and prediction that increased demand for satellite launches would be realized in the early 21st century were a large part of it. Moreover, quickly reachable technology and business goals perception created by the contractors, helped to create enthusiasm. Cost, schedule and performance indicators were all predicted too optimistic. Although there were a lot of failures, it remained clear that reusability is the answer to significant future savings. NASA has been supporting technological developments in this direction. However, technology investment means that returns are long term. In short-term, savings can be achieved via regulatory, policy and operational changes (Kaplan, 2002, pp. 1181-1182).

The fundamental difference when comparing reusable and expendable launch vehicles is that once RLV fulfils its mission, it returns to Earth for multiple future uses, while ELV is only used for one mission. There are multiple reusability concepts proposed such as single stage, multiple stages, horizontal landing, vertical landing, horizontal or vertical take-off and others. The main factors to be considered while designing RLVs are their composite, light weight structure, a well-developed heat shield used for re-entry protection, improved propulsion and propellants, increased range and payload capacity (Bhavana et al., 2013, pp. 1-2).

For a space logistics system to be sustainable, vehicle reusability must be analysed. If space operations continue only on a limited level, then expendable approach will be the way to go for the future planning of space missions. However, if operations to space are expanded, reusable approach shall be preferred. There are several arguments to support this statement, such as the stagnation of the ELV commercial launch market, reusable system domination for terrestrial use, and even conclusion of the Air Force Scientific Advisory Board, stating the need to move to reusable systems to meet the future national space launch needs (Snead, 2004, p. 10). Expendable systems have generally not been found more economical and safer than reusable systems, which are preferred across a range of applications and technologies for safety and economy. This is especially the case in transportation where most of the things are reusable from cars, to aircrafts, with exception of an ELV. Expendable systems require additional manufacturing, storage, transportation and sales costs per cycle in comparison to reusable systems. This puts expendable systems at a disadvantage unless no reusable system exists (Snead, 2004, pp. 11-12). This is still the case nowadays, and will be further analysed in this chapter.

The Figure 20 represents the choice of continuing the current space launch paradigm of ELVs use, or to pursue the new greater promise paradigm of RLVs. The main questions are, if this "breakthrough" exists (Snead, 2004, p. 12), and which option is a better choice for the immediate future. While some argue that RLVs are better, others support new ELVs based on economics of development, production and operations of these systems (Snead, 2004, pp. 12-13). Wertz (2000, p. 14) concludes that the major driver of design and construction of new vehicles should be economics rather than philosophy. He includes that new ELVs are not likely to present significant safety and economic advantages over RLVs.

Figure 20. Technology "S" curve depicting the need to transition to a new space access paradigm



Source: Snead, *Architecting Rapid Growth in Space Logistics Capabilities*, 2004, p. 12.

From the curve, we can see the existing space access development due to learning and new technologies through time. The curve is ascending and comes to the point marked “now”. This is a breaking point from which a society can proceed in two ways. It can either continue using existing technologies which leads to a flat curve, or find a completely new approach, technology, breakthrough, which creates a new curve and brings further development.

6.4 Cost of Reusable and Expendable Launch Vehicles

It is generally assumed that launch costs will be dramatically decreased with reusable launch vehicles, because vehicle is not “thrown away” every time it is used (Wertz, 2000, p. 1). This might not always be the case, according to Ben Goldberg, the director of technology at the company Orbital ATK. On a recent panel, he expressed scepticism about the business case for RLV. His team ran a study and concluded that RLVs are not the best choice for orbital launches. RLVs have the most benefit with suborbital flights as it is easier for them to return due to lower thermal loads. In this way, the flight rates can be increased and the launch costs decreased. Some main cost differences between reusable and expendable vehicles will be analysed below (Berger, 2016).

It all begins with costs of development, which are the amortization amount per launch of the non-recurring development costs. They are spread uniformly over the total number of launches. Fixed amount is assumed to be paid on in equal payments at an annual interest rate. Non-recurring development costs will be higher for reusable vehicles as more components have to be developed, and development itself is more demanding (Wertz, 2000, p. 3). For

example, RLVs must have advanced heat shielding to allow it to re-enter the atmosphere multiple times. In addition, we have long experience with ELVs, while there are still some technologies that would need to be developed for RLVs (Butrica, 2006, p. 301).

Following the stage of development, there is the recurring production cost of a vehicle. Cost model in this part differs for an ELV and an RLV. For expendables, the recurring production cost of the vehicle is modelled as a classical learning curve, which means that each successive vehicle will be less expensive to build. The learning curve accounts for improved understanding of building the vehicle (i.e. learning), economies of scale, the ability to make specialized tooling, and set up production lines with production of larger quantities (Wertz, 2000, p. 3). With ELVs, constructing each vehicle is a recurring expense. On the other hand, recurring production costs favour RLVs, as construction costs are part of the upfront costs, which are amortized over each future launch (Butrica, 2006, p. 301). Assumption that the entire fleet is built at one time and depreciated over their lifespan is used. Reusable vehicles are also more sensitive to interest rates, as most of the money is spent up in advance. They are also more affected by interest and inflation rates than expendable vehicles (Wertz, 2000, p. 3-4).

Total cost of flight operations per flight which include on-pad test and checkout, payload mating, consumables, flight operations, and facilities cost are expected to be higher for reusable vehicles due to added launch complexity. It has to go through more operations procedures, because it has to be recovered and returned, and all the systems have to be checked prior to launch. Historically, high operations costs have occurred partly because of the effort to hold down the development costs. In general, operations costs can be reduced by spending more on nonrecurring development and creating a vehicle which does not require repetitive operations (Wertz, 2000, p. 4).

Recovery and refurbishment costs are applicable only to reusable vehicles or vehicle components. They include the actual recovery and return to the launch site. Refurbishment presents the cost of all inspection, cleaning, maintenance, re-tests, re-certification, and return to the launch site. When RLVs become older, more components will need to be re-tested, replaced or re-built. Comparatively, the Space Shuttles solid rocket booster's recovery and refurbishment cost was approximately equal to manufacturing cost. Insurance cost can be estimated as a percentage of the launch cost, which is typically around 15 per cent. Due to high non-recurring costs, reusable launch vehicle cannot afford to spend a lot on insurance, and, consequently, they should be made significantly more reliable than expendable to be economically feasible (Wertz, 2000, p. 5). Fundamental differences are shown in the Table 5.

Table 5. Comparison of Expendable vs. Reusable Launch Factors

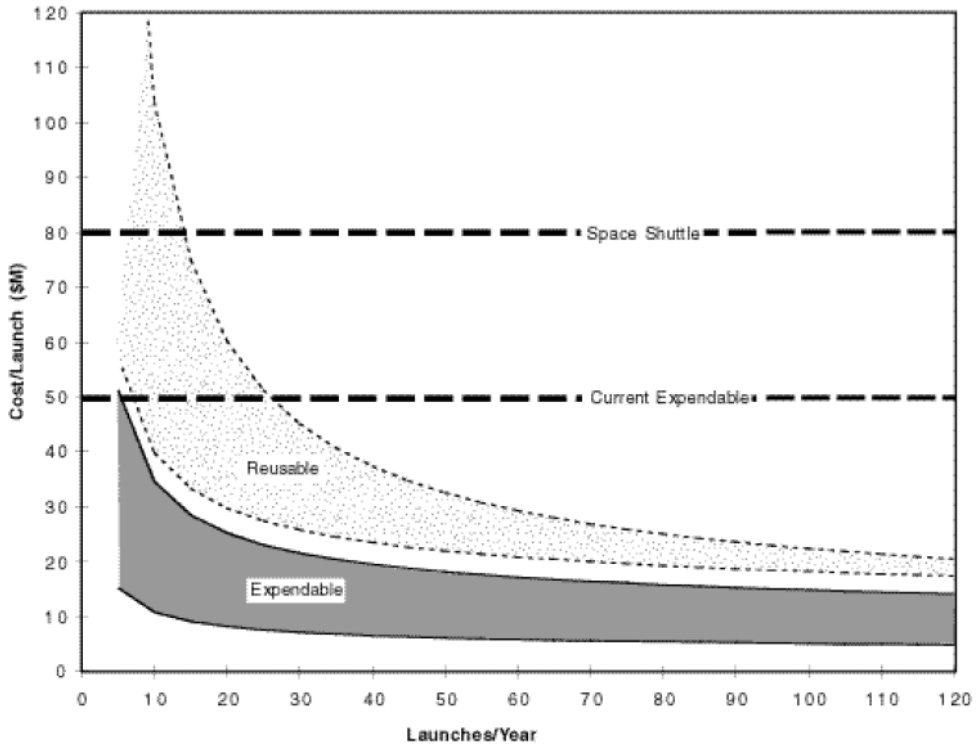
Exp	ReU	Factor	Discussion
X	X	Amortization of nonrecurring development cost	Higher for ReU due to larger nonrecurring
X	X	Exp: Recurring production cost ReU: Amortization of production cost	Exp uses learning curve; ReU is more complex and expensive to produce; Amortization rather than recurring production is the major ReU cost savings
	X	Recovery cost	0 for Exp
	X	Refurbishment cost	May be substantial for ReU; 0 for Exp
X	X	Flight operations	ReU has more complex systems; more expensive check-out and recovery
X	X	Vehicle insurance	Depends on both replacement cost and reliability; Exp or ReU could be cheaper

Note: * Exp = Expendable Vehicle; ReU = Reusable Vehicle

Source: Wertz, *Economic Model of Reusable vs. Expendable Launch Vehicles*, 2000, Table 1.

The projected cost of an ELV for the expected launch rate (10 flights per year for this example) ranges from $10 to $35 million per launch. On the other hand, the projected cost of an RLV it ranges from $35 to $90 million per launch. If the launch rates increase dramatically over time, the curves become relatively flat with the ELV dropping to $5 - $15 million per launch and the RLV to $20 – $25 million per launch (Wertz, 2000, p. 9). However, according to Bhavana, Mani, & Prarthana (2013, p. 4), the general cost estimations for ELVs vary from approximately $15,000 to $20,000 per kilogram in comparison to RLVs, where this number is much lower, from $200 to $2,000 per kilogram. Launch costs for RLVs and ELVs are represented in the Figure 21.

Figure 21. Cost per Launch vs. Average Launch Rate from 2001- 2015



Source: Wertz, *Economic Model of Reusable vs. Expendable Launch Vehicles*, 2000, Figure 2.

The costs of SpaceX are approximately $37 million to build, fuel, and launch a Falcon 9 rocket (Mosher, 2017). According to Clark (2016), SpaceX intends to reduce the price with reusability by 30 per cent. This amounts to $43 million per flight compared to the current $61 million which is published on the company's website.

In conclusion, ELVs will have an economic advantage over RLVs until launch rates increase by well over 100 times the current rate. Future ELVs have the potential of dropping launch costs by a factor of 5 to 10 compared to current ELVs. The fundamental question with RLVs is whether amortizing the costs over multiple flights is worth the increase in costs in most of the remaining categories (Wertz, 2000, pp. 13-14).

6.5 Dual Pricing and Cost Environment

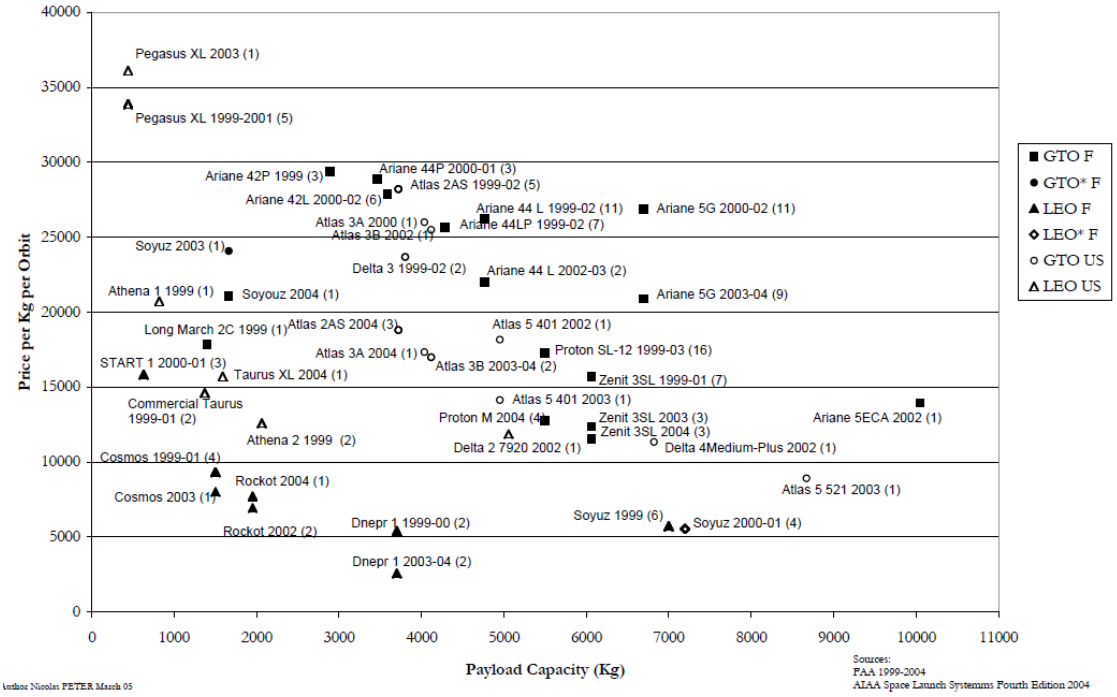
Cost of launches will remain high if launch vehicles will have a dual pricing/costing environment. This occurs when companies set prices according to market conditions for commercial launches, and different arrangements for customers such as governments. Prices for governments are usually set higher, since it is important for reasons such as politics and security, for the governments to keep the production lines running (Hertzfeld et al., 2005, p. 14).

There are also large differences when comparing the costs. Two cost approaches were conducted on the development of the Falcon 9 launch vehicle. The first one was traditional NASA environment/culture approach, and the second, commercial development culture approach. The difference in approaches are mostly technical inputs, and cost plus vs. firm fixed price contracting. Analysis performed in the late 2010 showed that based on NASA environment, the Falcon 9 launch vehicle development would have cost $3.977 billion, and when technical inputs were adjusted to commercial approach, the costs would have been $1.695 billion (National Aeronautics and Space Administration, 2011, pp. 2-4). SpaceX attributed cost efficiency to a few primary cost factors such as workforce, organizational complexity, and infrastructure. The main point of the above categories is that with reduction of total workforce, management layer number and infrastructure number, costs can be substantially reduced in comparison to traditional NASA environment (National Aeronautics and Space Administration, 2011, p. 3).

In case of the USA, the federal policy treats R&D costs as "sunk", or unrecoverable. Agencies usually charge "marginal costs", which are not the same as private business would calculate. The government usually takes average annual budget of the program and charges according to average cost per year per unit of output. Private company's calculation would be very different. First, a private company has to recover its net investment in R&D, manufacturing facility and equipment. Furthermore, a private company will add a profit margin to its costs and try to maximize the profits depending on competition, or the lack of it. The actual cost of privately funded vehicle will not be the same as the price charged to the client. If there is little to no competition, the price can be much higher. However, if a company is a new market entrant, or has excess inventory, it can even charge a short-term price which is below their cost. This, of course, does not work in longer term. Therefore, if there is little competition it is possible that the costs of accessing space can be lower, but the price may not reflect this (Hertzfeld et al., 2005, p. 26).

It is often assumed that development of a new low-cost launch vehicle will reduce the costs of access to space, which is only partially correct. A study made for the Titan and the Atlas launch vehicles showed that the vehicle presents only about half of the total cost. The remaining costs are divided among operations (tracking, data handling etc.), which present 30 per cent, payload integration with 5 per cent and "other" government costs with 15 per cent. However, new private companies estimate that vehicle manufacturing costs are close to 75 per cent of the total costs. This is a result of efficiencies found in overhead and in operations such as payload integration, tracking and data handling. Price of the launch will also be highly affected by customization. Each launch is unique and standardization of it is one way companies will try to maintain lower prices. Research conducted by Federal Aviation Administration shows the connection of price per kilogram to orbit with payload capacity for commercial launches, in the timeframe from year 1999 – 2004 (Hertzfeld et al., 2005, pp. 27-30). Results are presented in the Figure 22.

Figure 22. Domestic and International Launch 1999-2004



Source: Hertzfeld et al., *Launch Vehicles: An Economic Perspective, 2005*, Figure 1.

From the Figure 22, we can see the downward slope of the data points. This means that the higher payload capacity, the lower price per kilogram is. This fits two economic observations (Hertzfeld et al., 2005, p. 31):

- Downward sloping demand curve is a normal curve for goods and services, and
- As production quantity increases, the average cost per kilogram decreases.

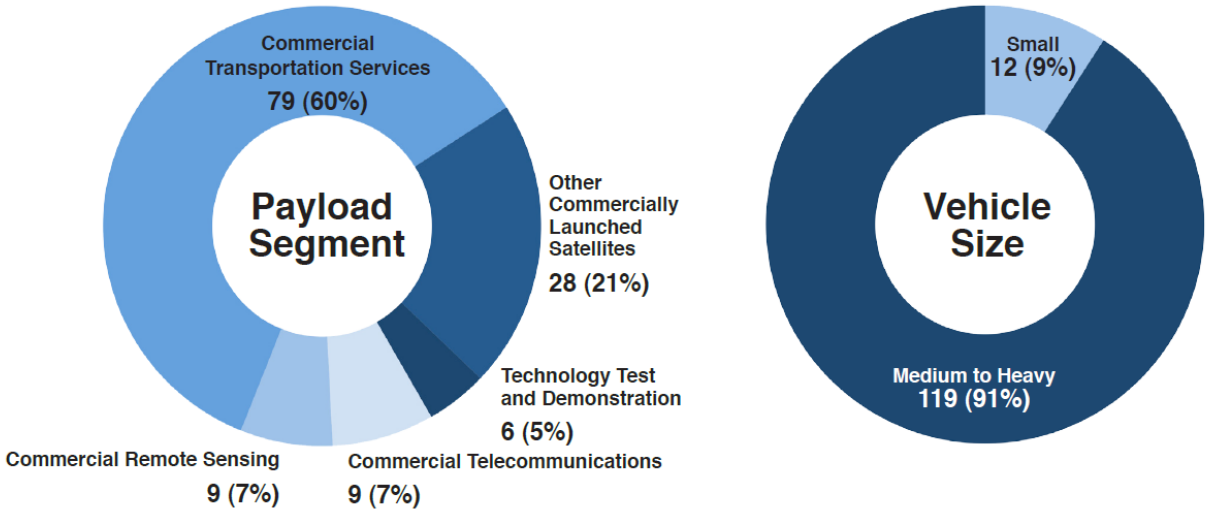
Additionally, we can also notice that Ariane launchers are at the top of the price range and Russian vehicles are priced lower than others. This is due to economies of scale and difficulty to establish a price related to true costs in a historically non-market economy as well (Hertzfeld et al., 2005, p. 31).

7 FUTURE DEMAND PREDICTIONS

7.1 Existing Markets

In 2015, global spending on space activities amounted to approximately $323 billion (Canis, 2016, p. 1). Approximately 80 launches (annual launches market) are serviced by 27 operational space launch systems and there are additional 14 in development (Hempsell & Bond, 2013, p. 434). Therefore, more funds are being spent worldwide on acquiring space access capability, than can be justified by the global launch market value. Launchers market is about double the launches market. This affects the prices launch systems are operating at, which are roughly half the true economic cost per launch (Hempsell, Aprea, Gallagher, & Sadlier, 2016, p. 3). 60 per cent of non-geosynchronous orbit (hereinafter: NGSO) launches in the next 10 years are projected to be a part of commercial crew and cargo program to the ISS. This also includes launchers that are still in development. Other commercially launched satellites mostly include government satellites that will be launched commercially at predicted 21 per cent share, followed by commercial remote sensing with 7 per cent as well as commercial telecommunications. Commercial communications are expected to decrease in 2018, due to full replacement of orbital assets for telecommunication constellations, such as Iridium and ORBCOMM. Distribution is presented in the Figure 23 which shows that forecasted vehicle size predicts domination of medium to heavy vehicles at 91 per cent compared to small vehicles with only 9 per cent share.

Figure 23: Distribution of Forecasted Launches by Payload Segment and Vehicle Size

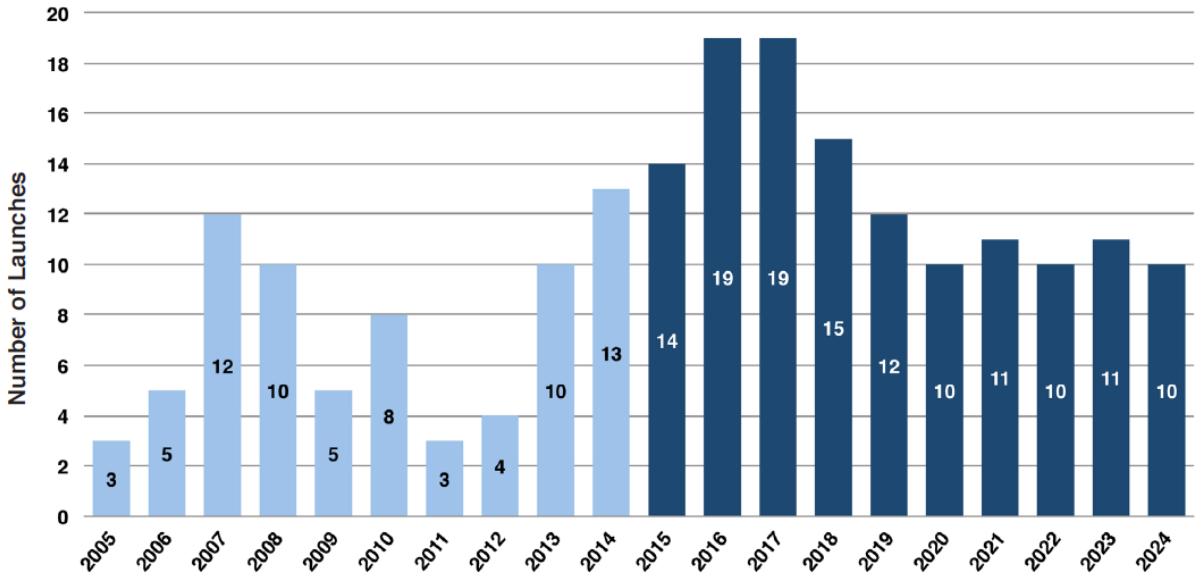


Source: Federal Aviation Administration, *2015 Commercial Space Transportation Forecasts*, 2015, Figure 10.

Projections for mid and far-term launches are based on publicly available information, estimates of satellites end of orbit life, and replacement requirements. Figure 24 presents

historical commercial launch numbers to NGSO and projected launch plans (Federal Aviation Administration, 2015, p. 23).

Figure 24. Commercial NGSO Launch History and Projected Launch Plans



Source: Federal Aviation Administration, *2015 Commercial Space Transportation Forecasts,* 2015, Figure 11.

NGSO telecommunication satellites that were launched in 1990s and 2000s had a life cycle estimation of four to seven years. Most of them are still operational and have exceeded their design life by two or three times (Globalstar, Iridium, ORBCOMM). These satellites will continue to serve their purpose. Most of the new satellites prepared for launch, have design life estimated at 15 years, which places the replacement period far ahead. If any of the existing satellites will need to be replaced before the new generation is launched, they will most probably be launched as piggyback payloads, unlikely to generate demand for a dedicated launch. Similar predictions relate to remote sensing satellites. Approximately 800 commercial remote sensing satellites are projected to be launched through 2024, which will mostly be microsatellites launched as secondary payloads, and will not generate new launch demand. This may change with the development and availability of very small launch vehicles (Federal Aviation Administration, 2015, pp. 32-35). Small satellite launch numbers had over 40 per cent annual growth since 2012. Market is becoming very attractive to commercial ventures as well as governments. Due to increased interest in nanosatellites, some ventures are specializing in small launchers dedicated to this specific market. This may turn the demand away from satellites being the secondary payload on large launchers (Doncaster & Shulman, 2016, pp. 13-16).

In the next decade, 60 per cent of the predicted launches are planned for commercial cargo and crew transportation services, followed by other commercially launched satellites and commercial remote sensing. The peak of launches will be achieved in 2015 - 2017, due to planned replacement of Iridium satellites. For the years after 2017, no telecommunication

primary payload is planned after the completion of constellations replacement (Federal Aviation Administration, 2015, pp. 51-53).

7.2 Emerging Space Markets

Space industry has its cyclical side just like any other economic sector. Many mobile telecommunication systems financed in the 1990s went bankrupt or were never launched. There were two economic downturns in the last decade which effected space budgets on a large scale. However, it seems that trends are turning and space industry is beginning its cycle of growth. There are three main trends that can be seen. The first one is globalization impact, the second one is connected to the rise of private sector, and the third one is new emerging markets. Emerging space markets can be defined as the ones that are not a very significant source of economic activity today, but have a big potential for growth (Gortuna, 2013, p. 37). Space industry will likely develop in the following three areas (Pelton, 2012, pp. 16-17):

- Space tourism / Space adventures – that will allow people to go on suborbital flights.
- Commercial space transport – accessing the ISS or other stations and delivering payloads to orbit.
- Hypersonic transport – allowing executives and high-flying jet-setters to travel from one continent to the other in a few hours.

According to Gortuna (2013, p. 37), there are two additional areas that have major potential, on-orbit satellite servicing and private space exploration. There are many different future projects planned, but in this part, we will focus mostly on space tourism, on-orbit satellite servicing, and private space exploration.

7.2.1 Space Tourism

There is little question that space tourism target market is there, with waiting list of customers willing to pay for the experience, similar to companies producing exotic sports cars, costing more than $200,000 which have multiyear waiting lists for their products. Norman R. Augustine predicts that with the development of the industry prices will decrease through economies of scale, safety will increase and the flights will become routine (Velocci, 2012, pp. 50-51).

Over 500 people have flown into space in the past. Space tourism has the potential to drastically increase this number. The space tourism market has 3 main segments: terrestrial/high altitude, suborbital and orbital (Gortuna, 2013, p. 38). Usually, general perception does not distinguish between these segments. For example, orbital flight is much more complex than suborbital and requires approximately 25 times more energy (Lindsey, 2003). Price elasticity is a big factor and analyses show that ticket price set at around $50,000

would bring maximum revenue per year at approximately $785 million from nearly 16,000 passengers (Futron, 2006).

Despite all the hype and marketing connected to space tourism, long term success is very much dependent on safety of the vehicles. Today's safety level in passenger aircraft industry was the result of decades of R&D, testing and operational experience. If space tourism will remain only a luxury market, it is going to stay very limited, serving adrenaline seeking customers. In this case, there will not be many repeat customers since the costs and risk for additional flights will most probably not be accepted by the initial customers (Gortuna, 2013, p. 38).

On the other hand, the industry can evolve into a necessity for a business travel. One of the proposed scenarios is also point-to-point transportation. Great reduction in travel time may be achieved by connecting major cities with suborbital flights. For example, a regular airliner requires about 13 hours for reaching Tokyo from New York. The same flight can be performed by a suborbital vehicle on a ballistic trajectory in 1.5 – 2 hours (not including boarding and deplaning procedures) (ISU, 2008).

With space tourism, there are many challenges from the economic perspective. Industry cannot count only on millionaires as customers. It should be able to attract a wider public segment. Economies of scale and efficient operations are the key to lower prices. Suborbital segment may achieve this decades before orbital segment does (Gortuna, 2013, p. 39).

7.2.2 On-Orbit Satellite Servicing

Any classical business model for space ventures is limited by the supply amount that can be carried on the mission. Once the spacecraft's vital supplies are depleted, it can no longer function normally. A good example is the ISS, which constantly requires re-supply missions. Solution to this problem is a robotic system capable of repairing and maintaining the spacecraft, which would drastically increase mission lifetimes, change space risk management and increase the value of spacecraft by adding operational flexibility. A similar system is already used for in-flight refuelling which brought many benefits for military aviation missions, such as reduced mission costs and increased duration and range. As theoretical and technical foundations are already in place, economic feasibility is another question. There have been several attempts to enter this market from multiple companies, to service GEO satellites. However, standardization of satellite interfaces was one of the main challenges (Gortuna, 2013, pp. 39-40).

7.2.3 Private Space Exploration

The term private space exploration covers diverse set of topics. A relatively new approach to the industry is the emergence of business to business, and business to consumer markets,

where private sector serves as an end-to-end provider of space products and services. The two segments that are closest to this model are satellite telecommunications and satellite navigation. Entrepreneurship has always been present in the space exploration market, mostly focused on governmental contracts. Today, companies have managed to convince investors to invest in these technically and financially risky projects. Space entrepreneurs are prepared to take more risk than space agencies and they are running their companies in a very "lean" way (Gortuna, 2013, p. 41).

Many scientific experiments showed that space is abundant in resources from metals and other scarce resources on the Earth to infinite solar energy. There are already companies aiming to exploit them. However, before the real analysis of mining potential starts, the question of where the source of demand lies needs to be discussed. If the source of demand is on the Earth, there is high probability that terrestrial substitute will be in place before space service is operational (Gortuna, 2013, p. 41).

7.3 Suborbital Reusable Transportation Systems

Suborbital reusable vehicles (hereinafter: SRV) are mostly commercially developed and may carry humans or cargo. Companies producing these vehicles usually aim at high flight rates and low costs (Tauri Group, 2012, p. 1). According to Federal Aviation Administration (2015, p. 7), SRVs are designed to reach at least an altitude of 100 kilometres and enter space for a brief time. However, they cannot enter a sustainable orbit around Earth, due to lack of velocity. Some of the vehicles under development are listed below (Federal Aviation Administration, 2015, pp. 7-8):

- SpaceShipTwo (Virgin Galactic) – Space tourism vehicle with capacity for 2 pilots and 6 passengers. According to the company 700 people already placed $250,000/ticket deposits.
- Lynx (XCOR Aerospace) – Space tourism vehicle with capacity for 1 pilot and 1 passenger with a ticket price of $100,000.
- New Shepard (Blue Origin) – Vehicle designed to take-off and land vertically. It is designed to carry at least 3 crew members and lands with parachute assistance.
- Stratolaunch aircraft (Stratolaunch Systems) – Designed to be powered by six of Boeing 747 engines, and a multi-stage booster to carry payloads to orbit.

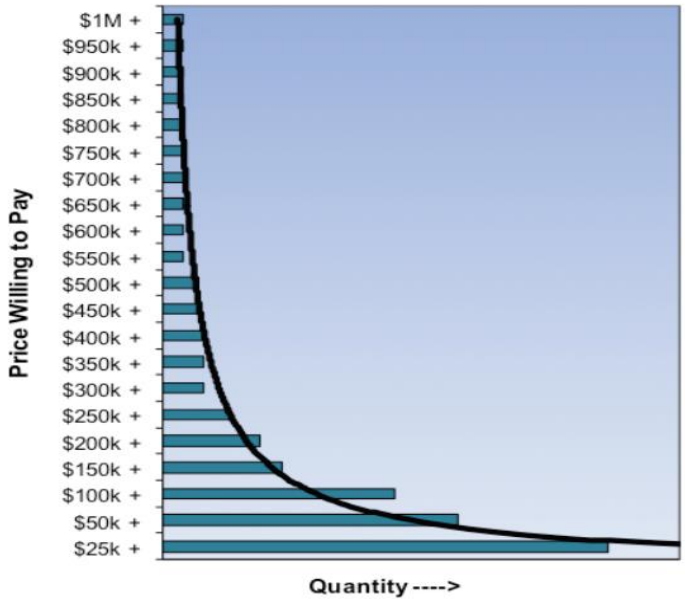
Most of the vehicle providers did not announce the exact flight rate details, or how rapidly they tend to increase them yet. They mostly aim at once per week to multiple flights a day (Tauri Group, 2012, p. 17).

According to the Tauri Group (2012, p. 2), the research performed divided demand for suborbital flights to eight markets. These are commercial human spaceflight, basic and applied research, aerospace technology test and demonstration, media and public relations,

education, satellite deployment, remote sensing, and point-to-point transportation. SRV demand is dominated by commercial human spaceflight. About 8,000 individuals with enough funds from across the globe are interested enough, so their spending patterns could lead to suborbital flight purchase. The interested population will grow at the same rate as high net worth population, which is approximately 2 per cent annually. Additional 5 per cent demand is expected from the space enthusiast's outside high net worth population (Tauri Group, 2012, pp. 3-4).

According to research conducted among high net worth individuals using surveys and open source materials, demand curve for future suborbital flights was evaluated. Demand is shown to be very steady. However, there can be many different events affecting it due to high uncertainty. With decrease of prices, demand is predicted to increase. The effect of prices on demand is shown in the Figure 25. The demand curve presents individuals with at least $5 million in investable assets (Tauri Group, 2012, pp. 4-5).

Figure 25. Price Elasticity of Suborbital Tickets for Individuals with $5 million in investable assets.



7.4 Space Launch System (SLS)

The Space Launch System (hereinafter: SLS) is a launch vehicle planned by the USA, intended for heavy lift science and human missions beyond Earth's orbit. Once commercial partners create a supply line to the ISS, SLS is also planned to serve as a backup transportation to the station. It is planned to be the most powerful rocket in the history and it is designed flexible and evolvable. This would meet a variety of mission's needs (National Aeronautics and Space Administration, 2012, p. 1).

The SLS will be more powerful than the Saturn V, which carried astronauts to the moon. There are two configurations planned. The first one has the ability to lift up to 70,000 kg, and the second up to 130,000 kg to the LEO. The vehicle will use proven hardware and manufacturing technology from the Space Shuttle and other programs which should significantly reduce development and operational costs. For the initial flights during development, it will use solid rocket boosters, which will be followed by industry competition for developing an advanced booster depending on the requirements (National Aeronautics and Space Administration, 2012, p. 2).

7.5 Skylon

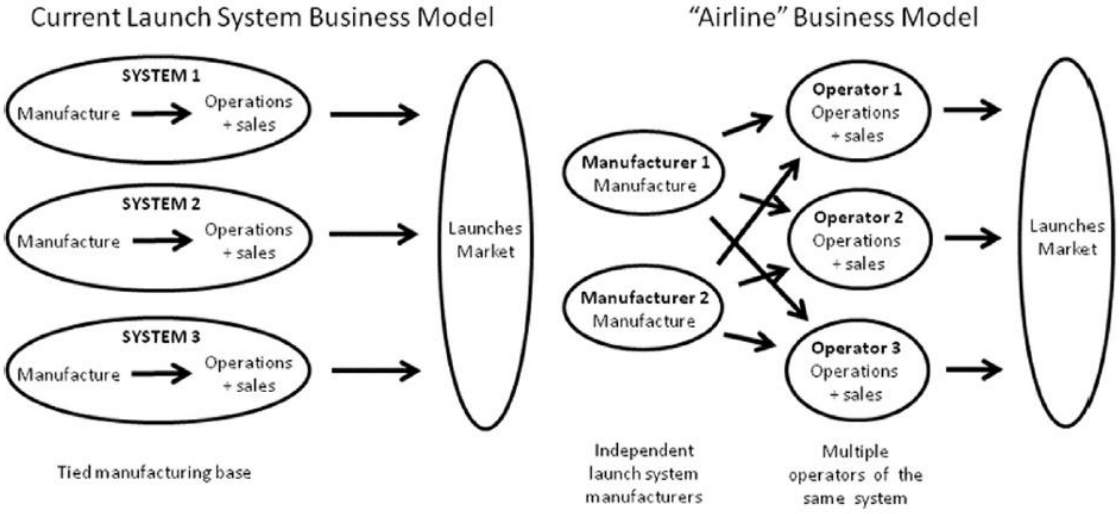
The Skylon is the next generation SSTO launch system concept, which is fully reusable. The main property of the vehicle is the air breathing rocket engine which is still under development. It is designed to take off from a runway like an ordinary aircraft and reach the LEO, carrying up to 15 tonnes of payload. Once it completes its mission, it returns by landing on the runway. The base vehicle itself cannot take payloads beyond the LEO, which is why it can have an additional upper stage propelled by hydrogen and oxygen. With the additional stage, it can deliver payloads of up to 6.3 tonnes to the GTO. After delivering payload to the GTO, the second stage can be recovered and reused for up to 10 times. During the tenth flight the upper stage is expended, increasing the payload to 8 tonnes.

10 per cent of GTO market payloads are in 6.3 – 8 tonnes range, which is captured by this approach One of the key objectives of Skylon is to fully commercialize space launch supply market. This means that the price charged for the launch covers all service costs including acquisition investment. To achieve this, the company relies on vehicle's reusability, single stage operations like regular aircraft, and increased reliability. If the standard launch business model is used, where manufacturer and operator are both a single business unit, then the resulting up-front investment required makes the entire business unviable. That is why the vehicle operators will address the space launch market, while Skylon manufacturer will be addressing launch vehicle market, by selling the product to organizations that require space access capabilities. Skylon manufacturer would spread the high development cost among many customers, creating a better return on investment potential. For operators, this would present much lower acquisition costs compared to "in house" development, and would be more efficient. In this way, the Skylon launch system would be attractive to both manufacturers and operators. Private equity investments have been the major funding driver of Skylon development. However, there has also been a significant public contribution made through ESA technology development programme (Hempsell et al., 2016, pp. 1-3).

Current and proposed (airline) business model are illustrated in the Figure 26. In the current business model of the launch services industry, manufacturer and operator are both a single business unit. This approach restricts operator's competition and can lead to market failure. Very few markets operate in this way. Although early aviation industry started with this

model, it is no longer used in the airline industry. Skylon business plan has been revolved around the airline business model. It allows launch service operator to be the anchor customer for manufacturer and spaceport launch complex. Similar to the airline model, manufacturer would sell the Skylon to operators at the same price. It would allow recovery of vehicle development costs that European government would not cover with its subsidies. They would be spread across the Skylon purchasers (Hempsell et al., 2016, pp. 2-4). Business model comparison is shown in the Figure 26.

Figure 26. Comparison of Current Launch System Business Model with Airline Business Model



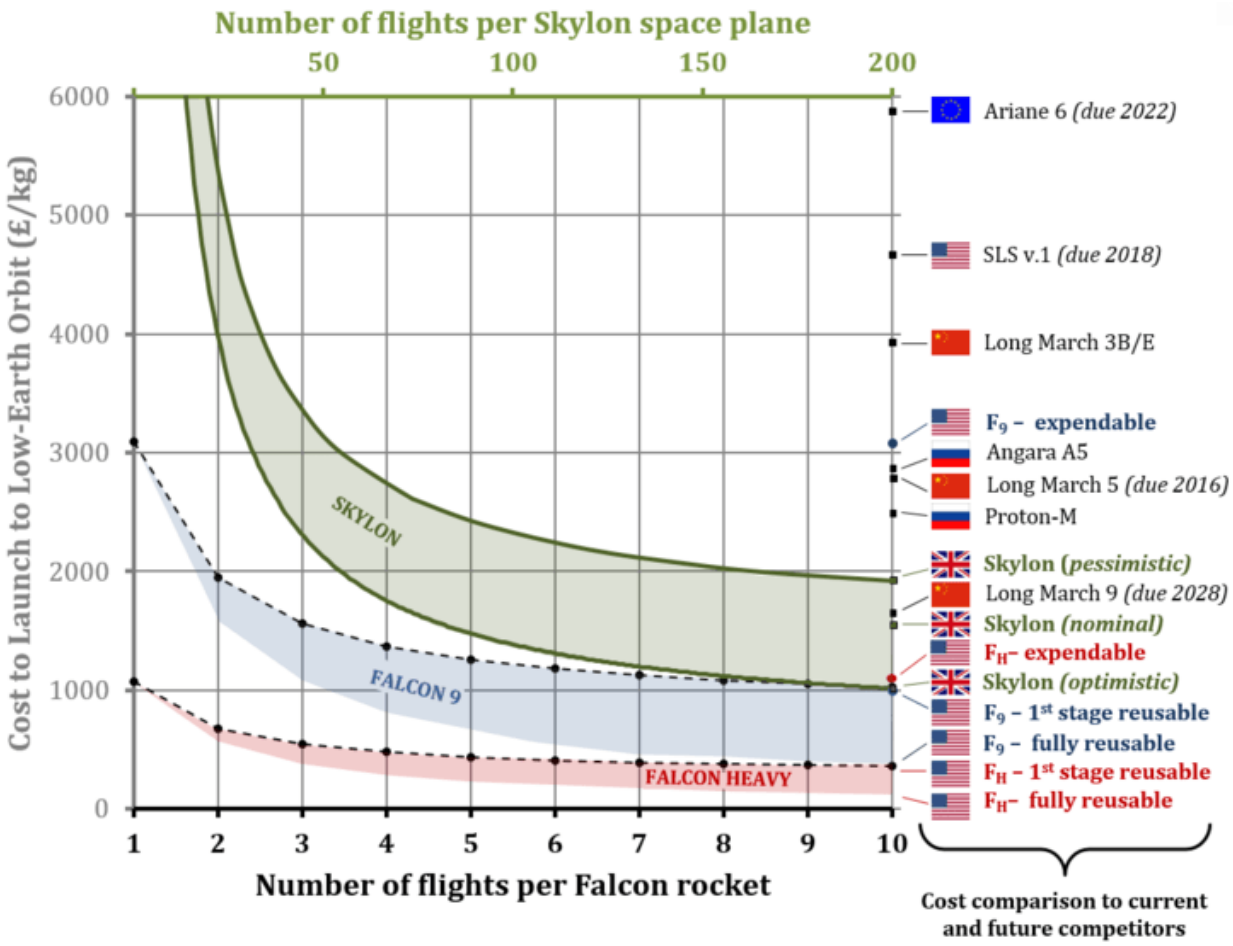
Source: Hempsell et al., *A Business Analysis of a Skylon Based European Launch Service Operator*, 2016, Figure 2.

The vehicle price would range from €3.6 billion to €19.2 billion if there is only one purchaser and €0.8 billion to €1.9 billion in the commercial scenario, where it is sold to multiple operators. There has not been a solution found to completely cover the development costs with sales to a single operator. In different scenarios, studies show that Skylon manufacturer has the potential for the Internal Rate of Return (hereinafter: IRR) that is close to public-private partnership levels (approximately 10 per cent), if the sales price is €1.5 billion and vehicle demand is more than 30 units (this also includes a €5 billion government subsidy). A government subsidy would surely be required to attract commercial investments and de-risk the business (Hempsell et al., 2016, p. 6).

However, comparisons have been performed between the most promising future projects the Falcon 9, the Falcon Heavy and the Skylon. In the Figure 27 we can see that the Skylon is vastly more expensive and requires many reuses before its costs decrease to the same level as the other two competitors. Even if launch costs would drop significantly, it is very questionable if the commercial market for launch services would grow enough to provide

Skylon with the use required to drive down its overall costs. We also should keep in mind that current launch numbers worldwide are below 100 on average (Ashley, 2015).

Figure 27: Cost Comparison of Skylon and Falcon Launch Vehicles



Source: Ashley, *Spaceplanes vs. Reusable Rockets – Which Will Win?* 2015, Figure 2.

According to Ashley (2015), there are several reasons why the Skylon will not be competitive. It costs 30 times more than Falcon 9, or 20 times more than Falcon Heavy. Hypothetically, it should be more reliable. However, such a large cost difference also has a great effect on the insurance cost, which drives up operating costs even further. Its innovative engine is supposed to be a great advantage over its competitors. However, using an exotic and relatively expensive combination of jet and rocket propellant, refuelling the Skylon would cost 6 times as much as the Falcon 9, and twice as much as the Falcon Heavy. The Skylon also requires 5 km long runway. Meanwhile, Falcons could be launched from an oversized helipad (Ashley, 2015). From the Figure 27 we can see that in an optimistic scenario, the Skylon would come close to the Falcons only at about 200 launches, which is a lot considering current global launches are below 100.

8 QUALITATIVE RESEARCH OF SPACE TRANSPORTATION SYSTEMS

8.1 Interview Details

In the final chapter I will present interview results, conducted with industry professionals on current state and future of space transportation systems. Interviews were conducted with 6 individuals, according to their area of expertise. Interview participants are listed below:

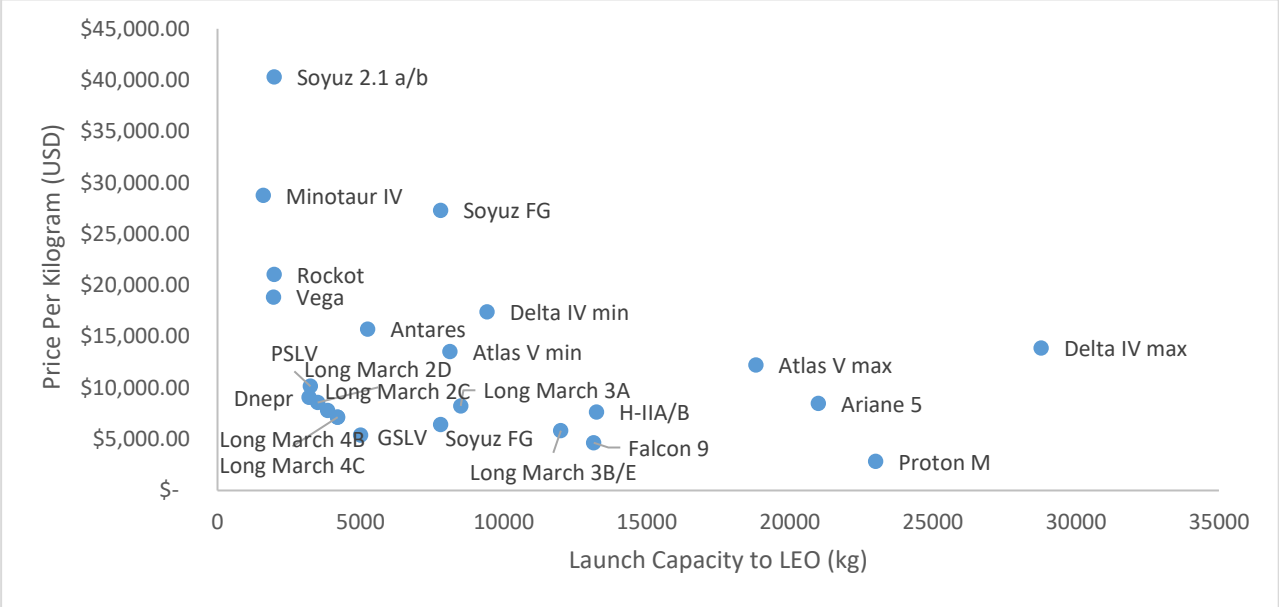
- **Andrei Sapera** – YGT in space economics at the European Space Agency (ESTEC).
- **Chris Dromard** – Founder of the New Space People organization, business network for the space industry's global professionals and companies.
- **Luca Del Monte** – Space economy manager at the European Space Agency.
- **Olivier L. de Weck** – Professor of Aeronautics, Astronautics and Engineering Systems at the Massachusetts Institute of Technology.
- **Pierre Lionnet –** Director of research at the Eurospace.
- **Tomaž Rodič –** Director of Slovenian Centre of Excellence for Space Sciences and Technologies.

According to findings in the theoretical part, the interview was structured to cover the most important subjects of the topic. The questions were divided in several topics, including current state of the industry and identifying its largest problems, current costs, potential cost reduction, launch vehicle reusability, new competitors on the market, sources of current demand, and future development of the industry.

8.2 Cost and Revenue Specifics

Space activity today is still very much connected with the governments. Unlike cars, trains and trucks, space transportation systems do not exist without governmental support. All the world launch sites are owned by the governments and all the activities are paid by the governments. It is still too early to talk about a completely commercial market. Currently, the average evaluated price of launching payload into space is approximately $10,000 per kilogram. It depends on the vehicle size and orbit of launch. Larger vehicles can achieve lower cost per kilogram when loaded at maximum capacity. I gathered the price assessments of the most common launch vehicles from multiple sources in the Figure 28. Price per kilogram in relation to launch vehicle capacity is illustrated. Launch vehicle data with approximate launch prices and their capacity shows, that the larger the vehicles capacity is, the lower is cost per kilogram. We can see that the price per kilogram decreases with the increase of a launch capacity.

Figure 28: Launch Vehicle Capacity in Relation to Price per Kilogram



The main space transportation systems cost drivers are development and operational capability. According to Lionnet, if there are not enough funds devoted to development, future launches will not be feasible. For example, the Ariane 5 development costs approximately €3.2 billion which are basically sunk costs. Nobody seems to be addressing the question of who is going to cover these costs. Launcher programs receive a direct financial support, in which some program parts are not connected to any development activity. Even when the launcher is already developed, the funds for the development keep coming in. These funds are used as subsidy to keep the launcher market price competitive. That means that every time the Ariane 5 is launched (€150 million overall for the recurrent part), the Arianespace uses €50 million to subsidize the launcher. It is believed that all the countries with launcher capabilities are using a similar approach.

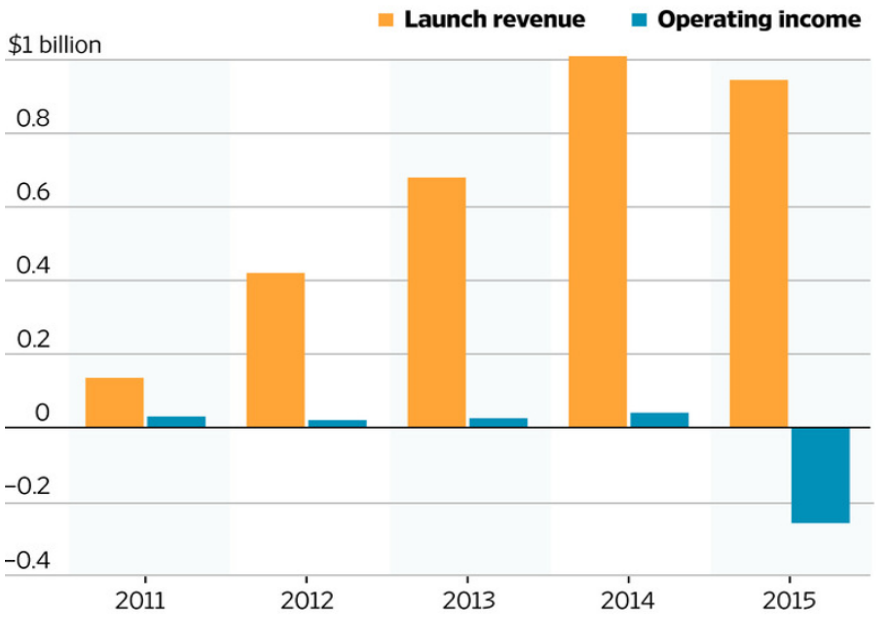
Lionnet believes that offering competitive prices with means of subsidies is a way to keep the launch activity going. However, finding a more efficient way of launching and decreasing costs is much harder. The Ariane 6 program is being designed to reduce the launcher costs. Multiple billion euros of public funds will be invested to make a cheaper launcher. Contrary to commercial industry, this investment will not be accounted for when discussing the cost per launch, as well as costs such as infrastructure, population migration, launch site security and others. Furthermore, political programs presented to the minister which include cost reduction, never state the cost of the current launcher. This means that they are trying to reduce the cost of a launcher, for which they do not know how much it presently costs.

The retired Space Shuttle is a very similar example. Cost approximations for this system differ greatly, ranging from $115 million per launch, up to $1.5 billion per launch, depending on evaluated information and methodology used when assessing the costs. The launch system

was intended to reduce the cost of spaceflight with reusability. However, it was much more expensive than the existing systems of that time.

Del Monte explains that in the old approach, a government or a space agency purchased the launcher and spacecraft from the private company, whilst in the new approach they only purchase the service. The interview participants all agreed that SpaceX is one of the most competitive launch service providers in the market today. In public-private partnership with NASA they successfully developed the Falcon 9 launcher, which has an advertised launch price of $60 - $65 million per launch to the LEO. SpaceX claims they decreased the cost to approximately one third of what it used to be. They are very lean when it comes to production, as well as documentation and administrative processes. However, when SpaceX is presenting its launch revenue, Lionnet argues they are not separating service revenues and launch revenue. They are clearly including revenue from NASA which is not associated to launch, such as development funds. SpaceX earnings are presented in the Figure 29.

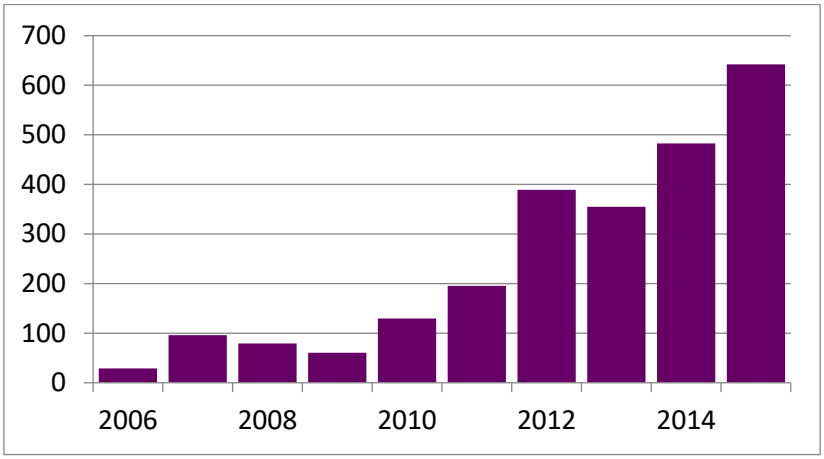
Figure 29: SpaceX Earnings



Source: Lionnet, *SpaceX Information Update*, 2017a, p. 3 (Reproduction forbidden, all rights reserved by Eurospace).

In the Figure 30, we can also see they received large amount of funds from NASA. They also launched most of the payloads for NASA, which might be an indicator that company's revenue streams rely too much on NASA, and that there is not enough demand in the commercial market.

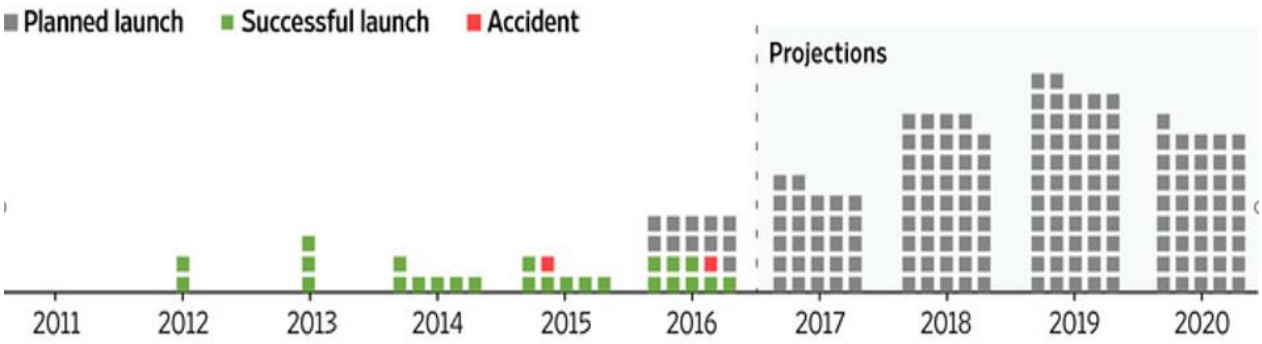
Figure 30: NASA Awards in Millions of €



Source: Lionnet, *SpaceX Information Update*, 2017a, p. 3 (Reproduction forbidden, all rights reserved by Eurospace).

Lionnet also pointed out SpaceX's optimistic future launch projections are a bit controversial. Historically, the peak of launch activity was between 1982 and 1991, and in this period Soyuz was launched from Baikonour more than once per month; Russians had 5 launch pads. At the same site, they also launched the Proton and the other smaller launchers. On average, Russia performed 20 launches per year and 40-50 in their best years, which is extremely hard to achieve. From SpaceX projections presented in the Figure 31 we can see they are planning 27 launches in 2017, which will clearly not be the case. Further on, they are planning over 50 launches per year in the years to come.

Figure 31: SpaceX Launch Prospects



Source: Lionnet, *SpaceX Information Update*, 2017a, p. 11 (Reproduction forbidden, all rights reserved by Eurospace).

The predictions for future revenue of SpaceX seem very unrealistic. The company is claiming that they are lowering the price of launch. However, apart from SpaceX statements, nobody knows if costs have truly been decreased. One assumption is also that they could be moving

toward dumping prices. Furthermore, as Del Monte points out, there are large differences in evaluations when SpaceX can reach the break-even point with its reusable launcher. SpaceX claims this will happen with approximately 10 launches, while European experts are more conservative, claiming if reusability will be successful it could be reached with around 50 launches.

Del Monte continues by listing some key differences between commercial markets. He states that for some nations, the USA included, it is common that military and governmental satellites are launched by the domestic company or government itself. It is a so called “captive market”. Countries are protecting their domestic market and creating a certain demand for the domestic companies. Europe, however, is different. Military or governmental satellite can be launched by other nations as well. For example, it is not uncommon for the European Eutelsat to ask for European public support, but when it comes to launch they will rather choose SpaceX as it is cheaper. This is also the case when building a satellite, where Eutelsat will also shop around and select the best offer for their requirements.

8.3 Reusability as a Sustainable Future Approach

According to de Weck, the highest cost of a launch vehicle is the first stage engine. The first stage is usually by far the largest and the most expensive part of the launch vehicle, with 50 - 70 per cent of launch vehicle cost. The second stage is usually not reusable. SpaceX strategy is to, firstly, re-use the first stage. Instead of treating it as a complete variable cost (regular expendable vehicles), a part of the first stage becomes fixed cost and can now be spread over multiple flights. The first stage is the most suitable for refurbishment not only because of its value, but also because it is less damaged as it comes from lower altitude at approximately Mach 5. SpaceX succeeded in landing the first stage and reusing it once. However, the important question is how long it will take to re-fly it, and what will be the cost of refurbishment once it becomes a standard. For example, Space Shuttle's engines were not exposed to the atmosphere re-entry much as they were behind the vehicle, but it was still very expensive to refurbish them. Moreover, Sapera believes the number of flights performed will be a key metric to be competitive with expendable launch vehicles. From Shuttle experience, reusability increased the cost instead of decreasing it due to very expensive refurbishment and other project factors as well, but the new SpaceX approach shows much more promise.

De Weck and Lionnet believe that desire for RLVs might be misguided and economically it might not work due to development and refurbishment costs. Efficient manufacturing of expendable multistage vehicles might be a better option. With automation, efficient structural design, and more efficient traditional processes, it might be more cost efficient than reusability. On the other hand, Sapera argues that the new SpaceX approach might contradict these statements. Compared to Ariane 6 €3.2 billion development investment, Falcon 9 development costs were only about $850 million. Furthermore, SpaceX is using the already paid missions to test and develop reusability. This means that after the customers’ payload is

inserted in the correct orbit, obligation to the customer stops and they can perform their tests on the launcher. This implicates that developing an RLV might not be much costlier after all.

In plans of creating an RLV future, Lionnet also mentioned that companies will also have to think about how this is going to change their business model. SpaceX initial business model was proposed in a way where they are building the launcher on their own, same engine is used in all stages and with this, they are exploiting economies of scale (the Ariane has different engine on each stage). If they start reusing the core stage, engines are being reused as well and economies of scale are lost. It becomes similar to aircraft maintenance, which creates a shift in their business model. Furthermore, highly tailored production economies of scale cannot exist and this is still the case today with most of the components. For the economies of scale to take effect, companies would have to produce more, and also change their production methods.

Following the multistage reusable vehicles, SSTO vehicles are the even more challenging. Most interviewees believe that SSTO vehicles are most probably not going to be launched anytime soon. De Weck goes on explaining that SSTO vehicles are very hard to design because of the structural mass fraction. To work, the vehicle must be light enough. Structural mass fraction of less than 8 per cent needs to be achieved. In other words, less than 8 per cent of your dry structural mass can be structure. This was tried by Lockheed Martin with their X33 vehicle, which was not successful even though it came close and achieved 10 per cent of structural mass fraction. SSTO vehicles might not be the best option unless some extensive material and structural advances in science will be made. Even if the weight is decreased due to lighter materials, total weight will not change much due to propellant it has to carry with, which represents a large part of the vehicle mass. Moreover, RLVs, including SSTO vehicles, require high launch rates. In case they were to succeed, launch rates have a large effect on materials used to protect the vehicle. During space flight the vehicle is exposed to very energy intensive conditions. It is cooled and heated with huge temperature variations, which extensively damage the vehicle (especially with orbital flight), and today we do not have a material that would last multiple re-entries to protect the vehicle. Furthermore, Lionnet believes acceleration technologies might have come to the point where there is not much more potential for development and a completely different technological breakthrough would be required. Sapera thinks that the only serious SSTO system in development is the Skylon. If the concept works, it is expected to be used mostly for LEO or lower altitudes, providing maintenance support and services with quick turnarounds.

8.4 Space Industry Development and Demand

Space launch industry is very government driven and political. According to Rodič, companies require approval from governments to launch a satellite, which must be received from the country of origin, as well as the country, where it is launched from. It takes a lot of time, effort, cost, licences and diplomatic arrangement, for payload to be launched by another

country. Even though it might be cheaper for the US payload to be launched with a Chinese launcher, the customer might not be willing to go through all the required processes. Space launch cannot be viewed purely as technical and economic issue, as there is a lot of politics involved in it. Furthermore, del Monte points out the International Traffic in Arms Regulations influence on not creating an entirely global supply chain in the space industry. Launchers are still treated as missiles and defence risk, which is why some components are very hard to source worldwide.

In the European space industry, logistics structure is highly complex and costly. In addition, every ESA member state is entitled to have some production involvement when developing a launcher, which is not cost efficient. According to del Monte, the objective till now was to produce a launcher which would ensure Europe a strategic independent access to space. With the development of Ariane 6 it has been added that the launcher must be affordable as well. In this regard, ESA made some key purchasing process changes turning to the industry with a new cost approach. First, the industry is asked for a cost-efficient consortium which must be approved by the ESA. ESA then advises the member countries if there are any companies in their jurisdiction that have been chosen by the ESA as contractors for launch vehicle production. In this way, the most cost-efficient companies will receive contracts and cost reduction is expected.

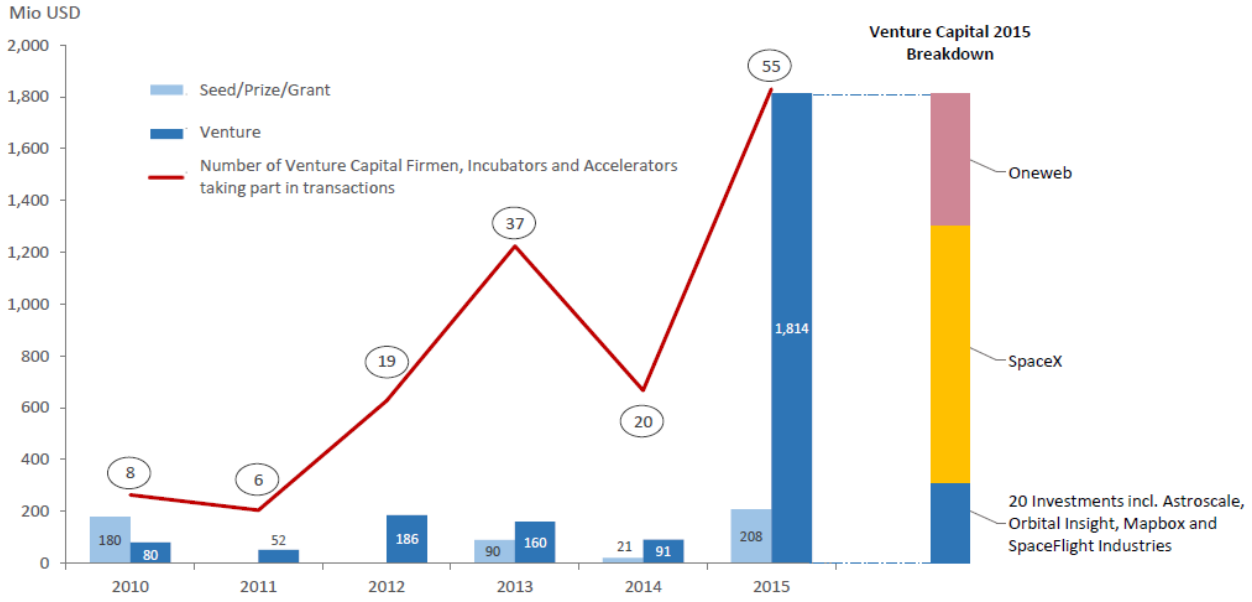
The space industry is also known for its very long lead times which can present a large obstacle for a customer, as they should reserve a launch at least 18 months to 2 years in advance. It is very different from terrestrial supply chains, where container can be shipped in a matter of days. As Rodič points out, it is not easy to get a piggyback launch for a smaller payload to the required orbit due to different mission types (height, inclination etc.). Furthermore, if the main launch customer has a delay in his payload delivery, others who are piggybacking will also have to wait, as well as the launch provider. This can sometimes take multiple years. Once launch provider loads the spacecraft for one launch, it is hard for them to gather a group for another one due to very different demand preferences. This presents a problem on supply side as well. On one side, there is competition between customers trying to launch their payload on a certain rocket but on the other side, it can be difficult to find enough of payload to maximize the space vehicle capacity. Customers are not very flexible, as there are limited orbit positions suitable for their satellite.

In this regard, small payload market is developing and there might be near term potential demand for small launchers, which take up to 100 kg of payload. If the planned price is around $10,000 per kilogram, it means a launch would be priced at about $1 million. They would solve the problem of customer specific orbit requirements with more flexible approach. However, Lionnet is not convinced that small launchers will work due to higher price per pound and low reliability. Basically, operations costs are similar to larger launchers and reliability is lower with a smaller launcher. The only way small launchers might work is with

aircraft taking them to higher altitude and releasing the launcher which goes to higher altitudes on its own, although in this case the separation stage would be very complex.

Market for small payloads is hard to define. If constellation of small satellites is launched, many satellites must be launched at the same time which cannot be the target segment. Small cube satellites built by universities cannot be the target market as well, as $1 million or more is generally a large amount to pay for academic institutions. Sporadic launch of small satellites might not be a real market, but only an opportunity used as a piggyback on another launcher. On the other hand, private venture investments which include small payload segment have increased. Rodič thinks that smaller launchers might present a supply for a specific niche market. As illustrated in the Figure 32, venture capital investments have greatly increased in 2015.

Figure 32: Venture Capital Investment in Space



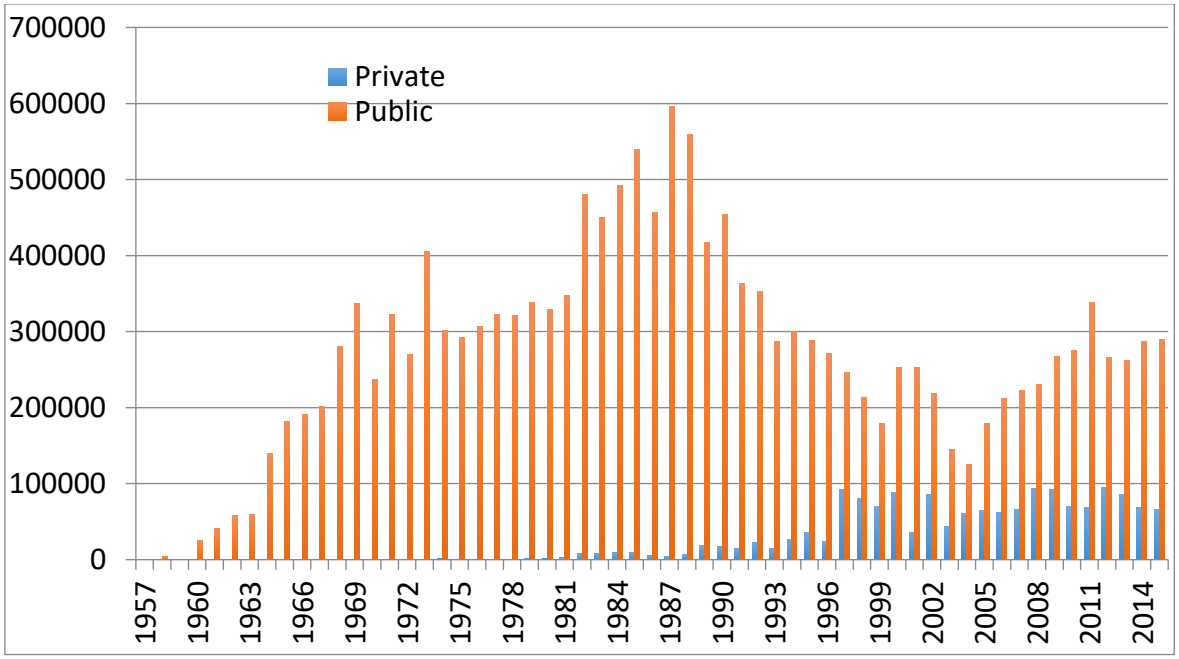
Source: SpaceTec Partners SPRL, *Financial Landscape for Space Related Ventures in Europe*, 2016, p. 12.

Dromard explains that business environment today is much more entrepreneur friendly than it used to be, and there are more investments in new companies and ideas. Mass production of the satellites is expected to be driving demand in the future, although there is not enough supply to launch all the requested payload currently, there are still launchers which are not occupied, as they are unable to meet the specific customer requirements. According to Sapera, companies producing low cost satellites are more price-oriented, and willing to try new cheaper launch options. New projects are planning large satellite constellations which will require great supply on the launch side. However, Lionnet believes demand is not the real question. When both the Space Shuttle (due to an accident) and the Ariane 5 were grounded, launchers were used almost to the maximum capacity. Demand might not be driving the

launcher production and is only making the best use of launchers available today. He states that it is a supply driven activity, with approximately 8 launch systems providing 80 per cent of launch activity worldwide. Even though there are many other launch systems available, they often cannot meet the specific demand requirements of the customers.

Lionnet explains that all domestic markets have overcapacity, as they require launchers for their own needs which they developed themselves. Most of the launchers are used only once or twice a year, except a few flagship launchers such as the Ariane, the Soyuz etc. That is why we have a supply driven overcapacity sector of which demand is not always satisfied. As an example, in the USA the Atlas V and the Delta IV are used exclusively for DOD and not available for commercial market as DOD is aware of their high cost. Selling them on the commercial market would require DOD to subsidize them, and they are only willing to do that if payload is launched for DOD. There are many situations where each country is using launchers for their own needs only. In Figure 33, public customer domination is presented.

Figure 33: Mass Launched (kg) by Public/Private Customers



Source: Lionnet, *The Space Economy,* 2017b, p. 5 (Reproduction forbidden, all rights reserved by Eurospace).

There are many new companies in the market developing new approaches to space launch. De Weck explains that even though a new entrant in the industry can have reliable space launch system, the initial assumption is they have low reliability. New companies start by transporting lower value payloads, and once they achieve a good track record, they can proceed with higher value payloads. With every successful launch their credibility increases. However, every failure sets them back significantly. Company requires at least 20 successful launches before it can afford a failure. If reliability is less than 95 per cent, company is not competitive in the industry, and the upper 5 per cent are the costliest. Reliability is also a very

important factor when it comes to insurance. Insurance companies assess risk depending on satellite value, in addition to the probability of failure, which also sets the price of insurance.

SpaceX has its Falcon 9 fully booked till 2018/2019, and customers are trying their new »cheaper« approach. Sapera states these are more risk-taking companies which do not mind new system not being as proved as others. The payload is also insured and private companies are willing to take this risk. It differs when it comes to payload that took many years to construct and is worth billions. This is usually connected to governmental project and they most likely choose the most proven space launch system.

For the near-term future of 5 to 10 years, the biggest potential for demand can be seen in Earth observation, communication, global satellite internet network, and everything related to collection and usage of data. Dromard adds that new companies will most likely start with smaller launchers focusing on niche markets and heavy launch vehicles will still be a governmental domain. He adds that tourism will develop at the beginning, and also gives good odds to private companies doing experiments in space (for example pharmaceutical companies tests). In suborbital flight segment, space tourism has a large near-term potential. Safety, legislation and cost reduction will present the biggest obstacles for the companies. A very important factor pointed out by Sapera is that governments and agencies will still support private companies. However, once the market is established, they will have to become customers to the private sector. In the launcher segment, access to payload is also becoming very important to customers. Nowadays, the customer should provide payload to the launch company months before the lift-off. In the future, they will need to have more time with the payload, providing it to the launch company much later in the process. Additionally, early access to results such as satellite connectivity and satellite data acquisition will also be required, so their investment can start paying off as soon as possible.

There is, however, a big problem, pointed out by Lionnet, which is not commonly addressed in the industry: it is the ignorance of full lifecycle costs from the first euro investment to construction, launch and final externalities. Reducing the cost of launch might not increase the number of launches or even the total cost from the full lifecycle perspective.

With the increase in launch activity, we also come to a point where space debris issue will need to be addressed. This is a very costly externality of using space. A good example is Envisat, a very large satellite the size of a bus that has stopped working in orbit. The satellite is still in orbit and every time it is close to another satellite, the operating satellite must manoeuvre around it, which lowers the satellite life time as it has to use propellant for movement. The lifetime of a satellite is driven by the quantity of propellant on board. If debris collides with a satellite it can have very serious consequences. Some governmental programs are starting to tackle this problem, but relatively little resources are dedicated to this issue.

CONCLUSION

Space transportation systems remain a mainly governmental domain. Enormous development and operational costs have kept them governmentally dependent. Furthermore, due to the nature of spaceflight, the industry remains highly regulated and countries still look at launch vehicles as potential weapons. Markets are still very much geographically limited and cannot freely expand globally. Space industry is still dominated by large companies bidding for governmental contracts. However, new competitors are catching up, challenging them with new approaches to space launch.

Commercial space industry is starting to take off, with the company SpaceX as the industry leader. With lean approaches and many high value governmental contracts won, they have been able to compete with the industry giants in this capital-intensive industry. They have been successfully resupplying the ISS, and successfully reused the first stage of their Falcon 9 launch vehicle. This is a major step towards reusability. However, the exact cost savings are still unknown. Although there are developments being made in the commercial launch industry, most of the financing is still received from the government and most launches are performed for the government as well. This might be an indicator that industry is still far away from being truly commercial, although there are some private clients booking launches as well. Starting with governmental cost-plus contracts, the industry is moving towards fixed price contracts, which brings more efficiency and cost control to the manufacturing process.

There is a lot of innovation present in launch vehicle development. At the beginning, performance was the key focus point when designing a launcher and attention was mostly focused on propulsion technologies. Today, we have a different situation where cost of spaceflight is one of the most important factors when designing a launcher. Although there are companies developing RLVs, ELVs are still most widely used. It is proven that staging is currently the most efficient way to insert the payload into orbit. Usually, up to 3 stages provide the best cost-performance ratio. Moreover, there have been many projects developing SSTO systems. However, with current technology, there is little to no chance this approach will work anytime soon. Reusability of launch vehicles might seem as the next logical step towards cost decrease, similar to terrestrial transportation modes. However, there are also good arguments defending mass production of ELV with high standardization and economies of scale use. Most of RLVs critics argue that development and refurbishment cost of RLVs will be too high and thus cannot compete with ELVs. On the other hand, if companies can use the already paid launches to test and develop their technology (SpaceX approach), and are able to refurbish the vehicle with relatively low costs, there might be a potential for RLVs. There are many good arguments for each approach. However, until the real costs are known, the comparison of costs will be highly inaccurate.

Findings of this research show that there are many political and national security motives behind space launch industry. Markets cannot develop in the same way as in many other

industries as space industry is highly regulated. Due to low volume of products and high customization of the products in the space industry, it is difficult to achieve economies of scale. As engines and many other parts are commonly hand built, a completely different (automated) manufacturing process would have to be implemented for economies of scale to take effect. Space transportation systems are developing. However, faster technological advancements have only started in this decade. Reusability technology, which is the most promising, has only been tested during the writing of this thesis. Due to competition, private companies as well as governments are forced to be more efficient and try different manufacturing and organizational approaches. Actual costs of launch vehicles are not known, but according to advertised prices, SpaceX offers the cheapest launch in the market. There is a potential for even further cost reduction, with the reuse of separate stages, as was demonstrated by SpaceX earlier this year. However, some industry professionals are sceptical that costs can be reduced with this approach as refurbishment might be too expensive. First stage, especially the first stage engine, is the most expensive part, and this is the starting component for reuse. Moreover, since it reaches the lowest altitude in comparison with upper stages, it also requires less refurbishment.

I believe the government will still have the main role in the future of space exploration and in new developments, as it was the case throughout the history with similar high-risk projects. Commercial industry will follow once routine practices are established and commercial markets can be created. There is, however, a very specific scenario in the present market for space launches. The industry is driven by oversupply of launchers. However, there are still issues with customers trying to find a suitable launcher, due to specific requirements for each payload. This makes it difficult to establish a mass market as a specific launcher cannot satisfy the diverse demand. There will have to be more standardization and automation in launcher and spacecraft production for the industry to expand. What would have to be examined further, are the real costs of spaceflight, which are very difficult to acquire. Additionally, focusing on launch vehicle and satellite full lifecycle costs would also be an interesting long-term perspective for the analysis.

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