Assessing the Disruptive Potential of Space Technology Concepts: Development and Application of an Evaluation Method

By Dimitrios Giannoulas

Disruptive Technologies

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Assessing the Disruptive Potential of Space Technology Concepts: Development and Application of an Evaluation Method

Diploma Thesis

Assessor: Prof. Dr. Hans Georg Gemünden
Co-Assessor: Dipl.-Ing. Aiko Karaschewitz
School of Economics & Management
Institute of Technology & Management

Supervisor: Egbert Jan van der Veen, MSc
DLR Institute of Space Systems
Department of System Analysis Space Segment

Dimitrios Giannoulas
Martr.Nr. 199380
Wörther Str. 33
10405 Berlin - Germany
Tel: +49 30 38308105
d.giannoulas@gmail.com
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Institut für Technologie und Management
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Prof. Dr. Hans Georg Gemünden
Fakultät VII (Wirtschaft und Management)
Technische Universität Berlin

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Eingereicht von: Dimitrios Giannoulas
Matrikelnummer: 199380
Studiengang: Wirtschaftsingenieurwesen
Anschrift: Wörther Str. 33, 10405 Berlin
Telefonnummer: +49 30 38308105
E-Mail: d.giannoulas@gmail.com

Berlin, den 23. Mai 2012

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Abstract

Since the introduction of the term *disruptive technologies* by Bower and Christensen in 1995, a multitude of research has been performed on how these technologies create new markets and provide more value for the customer in comparison to incremental or sustaining innovations. However, little is known about what disruptive technologies for the space sector are, the impact they can have on the space market and what benefits can be attained through them.

The first objective of this thesis is to develop a systematic technology evaluation method to support decision making in the evaluation of the disruptive potential of new technologies and technology concepts in the space sector. The second objective is to perform a practical application of the developed method and thereby validate it. This is achieved by means of a case study conducted within the frame of a larger research project on disruptive space technologies performed at the German Aerospace Center's Institute of Space Systems.

The developed method involves a combination of several technology evaluation techniques. The *Analytic Hierarchy Process* is utilized as a pre-selection process and as a method for determining the weights of the evaluation criteria. A *Delphi method* is used as a detailed evaluation process for technology concepts with a high potential for disruptiveness. For both techniques, *Concept Scoring* is implemented for the interpretation of the results. The case study results show a ranking of the 20 most promising candidates for disruption inside the technology domains *power, data handling, materials* and *propulsion*. The case study also provides proof of concept for the developed method and demonstrates its applicability and effectiveness.

Preface

This work represents my diploma thesis and constitutes the conclusion of my studies in engineering management at the Berlin Institute of Technology. It was written during the course of seven months of research at the German Aerospace Center's (DLR) Institute of Space Systems in Bremen, Germany as part of a major project on disruptive space technologies contracted by the European Space Agency and conducted at the DLR.

First and foremost, I would like to express my sincere gratitude to my supervisor and dear colleague Mr. Egbert Jan van der Veen. His guidance, his inspiration and his insights contributed to a large degree to this thesis and I really appreciate all the help he has given me during my stay at the DLR – both on and off the subject. He sparked my enthusiasm for disruptive (space) technologies and I will continue to advocate for them and research on the subject for as long as I can.

I would also like to thank the participating experts of the Delphi survey who invested many hours of their valuable time to complete the questionnaires. They did so without having any obligation and without expecting anything in return. For that I am grateful. Their participation and their expertise were crucial to the application of the evaluation method, the outcome of the case study and possibly for the development of a future disruptive technology in the space sector.

Last but not least, I would like to thank my parents for all of their support during the years of my studies. This thesis and my upcoming diploma would not have been possible without them.

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List of Acronyms and Abbreviations

Acronym	Explanation
A1	Attribute 1
AHP	Analytic Hierarchy Process
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DST	Disruptive Space Technology
DSTs	Disruptive Space Technologies
DT	Disruptive Technology
DTs	Disruptive Technologies
EQ	Economic question
ESA	European Space Agency
NASA	National Aeronautics and Space Administration
SEP	Social, Economic and Political
SMTs	Scanning, Monitoring and Tracking techniques
SQ	Social question
STEP	Social, Technical, Economic and Political
TQ	Technical question
TRL	Technology Readiness Level

1 Introduction

Every revolutionary idea seems to evoke three stages of reaction. They may be summed up by the phrases:
(1) "It's completely impossible - don't waste my time";
(2) "It's possible, but it's not worth doing";
(3) "I said it was a good idea all along."

- Arthur C. Clarke (1985)

1.1 Rationale

One of the most prominent theories within business, innovation and technology management literature deals with the disruption of dominant technologies and the respective markets by new technologies or so called disruptive technologies (DTs). This theory was first developed by Joseph L. Bower and Clayton M. Christensen (1995) and describes how new technologies enter a market and disrupt the status quo of that market by pushing the currently dominant technology along with its manufacturer out of the market. Since then, this theory has received high attention from industry leaders because of the great threat disruptive technologies pose to the incumbent technology leaders. The importance of the notion of disruption has evoked a great deal of research on the subject and a lot of literature has been written in the last two decades, most notably the work of Christensen (1997; 2003), Adner (2002) and Evans (2002). More recently, however, scholars have adopted the notion that the theory is not a-one-size-fits-all-theory and that it has to be adapted to the unique market dynamics of different sectors. Examples of these adaptions include:

- Education (Christensen, Horn, & Johnson, 2008)
- Medicine (Christensen, Grossman, & Hwang, 2009)
- Military (Mitchell, 2009)
- Gaming technology (Smith, 2007)
- Information technology (Peterson, Anderson, Culler, & Roscoe, 2003)

For the space sector, little to no research has been performed on how disruptive technologies emerge, how the disruption occurs and what benefit can be potentially attained through them.

The dynamics of the space sector are fundamentally different from the ones in classic consumer-driven markets. Space technologies have a far slower pace of evolution and the time span in which they emerge is often longer. The reason for this is that the space market is not defined by consumers and profit-driven businesses but rather by space agencies and, in extension, the governments they represent. Also, the hostility of the operating environment and the high cost associated with failure calls for materials and components with proven reliability so that a certain probability of mission success can be ensured. As a consequence, an inclination towards dependable and well-proven components can be observed and the entry of innovative technologies in the market is hampered. Currently, many space technologies only bear the potential for incremental and sustaining innovation. In order to achieve these minor improvements in performance, often a large number of resources are required.

Radical technologies, however, are key causal agents of disruption. Only new concepts, out of-the-box thinking and breakthrough technologies have the chance to bring up new momentum into space technology development. In this way, disruptive technologies might facilitate to innovate the space market. Benefits like lighter materials, higher performance levels and decreased production and integration costs are only some examples for possible outcomes. Disruptive technologies can change the layout of the space market and change the sector in a way that the present dominant technologies may become obsolete. The importance of innovative concepts and the difficulty of finding and implementing them are reflected not only by the introductory quote by Arthur C. Clarke on Page 1. Also supporting this is a quote from the European Space Agency's Technology Readiness Levels Handbook for Space Application (2008) who state that:

> The ability to make good decisions concerning the inclusion or exclusion of new technologies and novel concepts, and to do so in the absence of perfect information, is essential to success of many space programs. […] Numerous approaches have been developed to assist in meeting this management challenge, including the use of a variety of decision support tools. A critical step in all such methodologies, however, is the consistent assessment […] of various advanced technologies prior to their incorporation in new system development projects. (p. 1)

1.2 Research Objective

To date, there is no empirically tested evaluation method for assessing the disruptive potential of space technology concepts. The first objective of this research is to develop a systematic evaluation method that encompasses technology concepts from within the space sector as well as technology concepts from other industry sectors that can potentially be beneficial and work in a space related environment, so called spin-in technologies. This evaluation method is a generic process that is applicable to all technology domains of the space sector. The aim of the method is to provide decision makers with the necessary information needed for future technology development decision by providing an indication of the disruptive potential of a technology concept.

The second objective is the application of the developed evaluation method. The aim of the application is twofold. Firstly, it provides a ranking of the 20 currently available technologies that have the highest potential for disruptiveness inside four major technology domains of the space sector. Secondly, it serves as validation for the theoretically developed method and explores weak spots of the method. A detailed description of the application of the method and its aims is given in Section 6.1 of Chapter 6.

The two research objectives of the thesis are depicted in Figure 1 along with the respective aims of each objective.

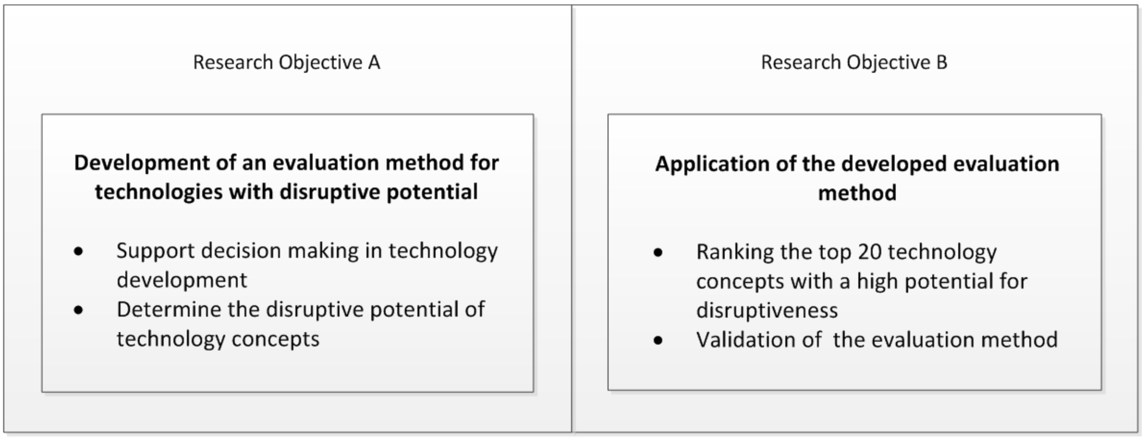

Figure 1. Research objectives of this work.

1.3 Conceptual Framework and Methodology

This research is conducted in the context of a major research project involving disruptive technologies in the space sector. The study with the title *Disruptive Technology Search for Space Application* is performed at the German Aerospace Center's (DLR) Institute of Space Systems on behalf of the European Space Agency (ESA). It has the goal of identifying technology concepts with a high potential for disruptiveness for the coming two decades for the space sector in order to support decision making in ESA's technology development strategy. To reach this goal, the following sequent steps are performed in the context of the DLR study:

1) Development of a theory on disruptive technologies for the space sector
2) Development of a search strategy and building of a database of technologies with disruptive potential that serves as a basis for technology evaluation
3) Development of a technology evaluation method for technology concepts with potential for disruptiveness

4) Application of the evaluation method in order to identify technology concepts with a high potential for disruptiveness
5) Formulation of a development plan for the identified technology concepts

This thesis is part of the DLR study and the scope is limited to the development of the evaluation method and its application, as defined in the research objectives. However, the development of the evaluation method cannot be regarded as an independent process. The theory on disruptive technologies in the space sector is an essential part of the development of the method since the method is based on the theory. Also, the development of the search strategy and its application are essential to the application of the evaluation method because the created database serves as a basis for the evaluation. The steps of the DLR study and the interconnections between them are shown in Figure 2. The red frame shows the parts of the DLR study that are object of this thesis.

The development of the evaluation method is based on the theory of disruptive technologies for the space sector as devolved in an earlier stage of the DLR study and depicted in Figure 2. This theory serves as background knowledge and influences the method development process. Furthermore, the development of the method is done by considering various technology evaluation methods and analyzing them according to space sector specifics.

The application of the method is done in form of a case study. This research design is chosen to document the practical application of the method in the context of the DLR project as shown in Figure 2. The nature of the application is both descriptive and exploratory, which are both valid for case studies (Yin, 1993).

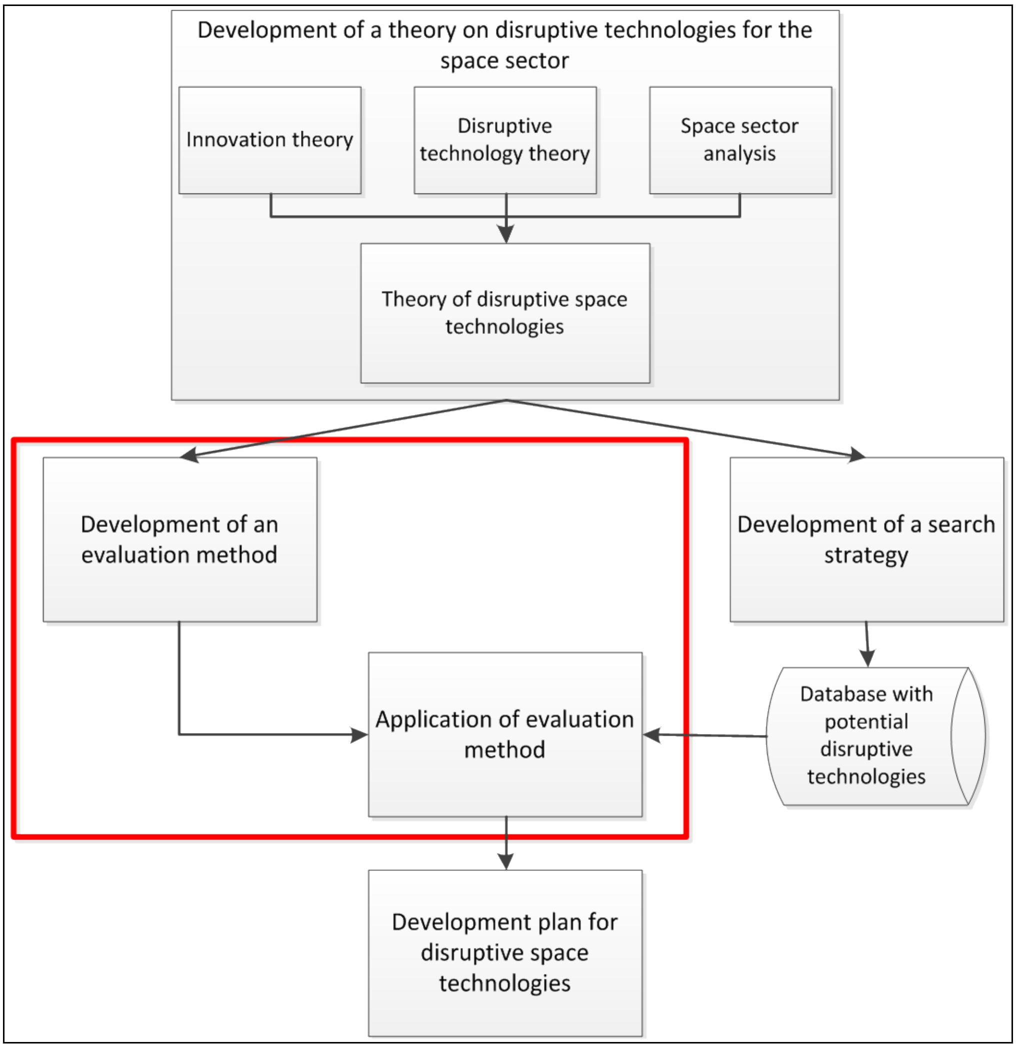

Figure 2. Structure of DLR research. The scope of this thesis is highlighted.

1.4 Research Layout

Chapter 1 serves as the introduction and gives an overview of what the rationale behind the research is, what the research objectives are and illuminates the interconnections between this research and the DLR study Disruptive Technology Search for Space Application.

Chapter 2 represents a review of business literature and provides the theoretical knowledge and the necessary information for the comprehension of the following chapters, especially the work that has been done in the DLR study. In Chapter 3, the work done in the DLR study is presented. Both these chapters serve as the theoretical background for this thesis. The reason for dividing the theory into two chapters is to emphasize the differences between theoretical knowledge that originated out of business literature and is widely accepted and accessible and theoretical knowledge that is done solely for the purpose of the research and is not yet public knowledge.

In Chapter 4 the methodology of the evaluation method design is elaborated. Chapter 5 presents the method as a generic process and gives explanations of the main features. A practical application of it in the frame of a case study is found in Chapter 6. Conclusions of the study that include limitations and implications for future research are discussed in Chapter 7. This chapter also gives recommendations for further steps that can follow the evaluation process.

Appendix 1 and 2 show the results of the surveys conducted in the case study providing a detailed example of a practical application of the evaluation method. The data also substantiates the voting of the experts and gives insights on their choices. Especially the comments given by the experts can be of great value for the potential future development of the technologies.

2 Theoretical Background

This chapter represents a review of literature and serves as the theoretical background of the study. It provides the reader with the necessary information for the comprehension of the following chapters, especially the work that has been done in the DLR study Disruptive Technology Search for Space Application and is elaborated on in Chapter 3.

The basic terminology of this study is defined in Section 2.1. The information given in this section is imperative for the understanding of the study and the introduced terms are used in almost all chapters. Section 2.2 represents a review of available methods for technology evaluation already in use in technology forecasting. It explains key features of evaluation methods in order to give a general overview of what they are and what they are trying to accomplish. In Section 2.3 the space sector infrastructure is analyzed with respect to technology development. It gives the reader an outline of what the space sector looks like and what its main characteristics and major differences to other sectors are.

2.1 Basic Terminology

2.1.1 Technology

Nowadays, the word technology is often associated with complex machinery, consumer electronics or software. However, the word "technología" (τεχνολογία) in ancient Greek has a broader meaning. The word's translation is twofold: "téchnē" (τέχνη), which is a craft or an art, and "logía" (λογία), which means the knowledge of a discipline. Several dictionaries provide different definitions for the word technology; however, they all focus on the following central themes (cf. Oxford Dictionaries, 2011; Merriam-Webster, 2011):

- The practical application of knowledge (knowledge is often referred to as scientific knowledge)
- Ways of making or doing things
- The sum of a society's or a culture's practical knowledge, especially with reference to its material culture
- The use of tools, machines, materials, techniques, and sources of power to make work easier and more productive

As can be seen, the meaning of the term technology is ambiguous and depends on the purpose of the word for the user. Therefore, regarding the present activity, the following working definition applies:

Technology is the practical application of scientific knowledge in creating tools, machines, materials and techniques, enabling or increasing the efficiency of human activities.

2.1.2 Innovation

While technology is any practical application of knowledge, innovation is often seen as doing something in a different way or as a successful exploration of new ideas. Innovation is a word derived from the Latin word "innovare" and according to several experts like Tidd, Bessant, and Pavitt (2005) or Ayres (1969) means: "to make something new". Therefore, this research uses the following working definition:

Innovation is the application of an idea or an invention that constitutes a change in the existing order.

It is important to note, because of a common misconception, that innovation is fundamentally different from invention. The typical distinction between an invention and an innovation is that an invention is a manifested idea and innovation is a successfully applied idea. Ergo, even the best invention has no economic value, if it cannot be turned into an innovation. Supporting this is the following quote from Roberts (1987):

"*Innovation = invention + exploitation*"

According to Francis and Bessant (2005), innovations can be classified into four broad categories called the *4Ps of innovation*: Product innovation, process innovation, position innovation and paradigm innovation. Tidd at al. (2005) give the following explanations for each of the 4Ps:

- Product innovation: Improvement in a product or a service
- Process innovation: Improvement in the way a product/service is created and delivered
- Position innovation: Improvement in the context, in which the product/service is introduced
- Paradigm innovation: Improvement in the underlying metal model that frames what an organization does

A second dimension to be considered is the degree of novelty involved, stretching from incremental to radical innovation. Doing something, that you do, better constitutes an incremental improvement (for example improving the performance of a car engine) while introducing a new thing to the world (for example a fuel cell powered car engine) can be considered a radical innovation (Tidd et al., 2005).

This study focuses only on radical product innovation. For a better understanding, Figure 3 illustrates how the 4Ps interact with the degree of novelty and shows the focus of this research. Innovation can take place on an axis running through from incremental to radical change; the area inside the circle maps the potential space of innovation (Tidd at al., 2005).

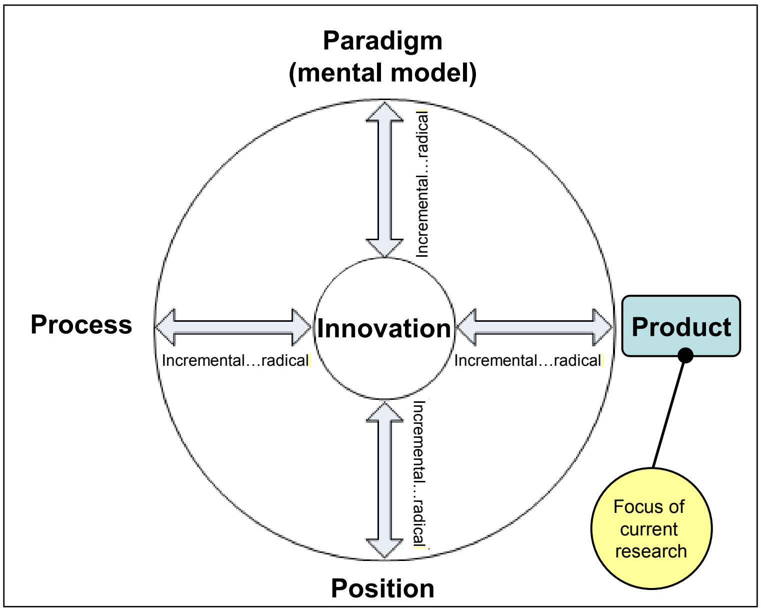

Figure 3. The wheel of innovation. Adapted from *Managing Innovation: Integrating Technological, Market and Organizational Change* (p. 13), by J. Tidd, J. Bessant, and K. Pavitt, 2005, Chichester: John Wiley & Sons.

2.1.3 Perceived Performance Mix

Companies marketing technologies attempt to satisfy customer demands. However, the demands and requirements for technology performance differ from customer to customer. In marketing literature, this heterogeneity in customer demands is called customer-perceived value (Yang & Peterson, 2004). The objective of this research is to determine the performance of a technology not on a single attribute but rather on a composition of different performance attributes like for example cost, speed, mass and efficiency. Taking both factors into account, a new concept under the term *perceived performance mix* is hereby introduced by the author. It represents a mixture of the relevant performance attributes as perceived valuable by a customer or a part of the market. This leads to the following definition:

The perceived performance mix is the mix of functional attributes of a technology as appeared valuable to the customer.

To further illustrate this, the following example is given:

Although the Discman originally was a Sony brand trade name for its first portable CD player introduced in 1984 (Sony Global - Press Release), it has become a generic trademark generally used for all portable CD players. With the introduction of portable mp3 players to the market in the late 1990s, the Discman market has undergone a significant disruption (Beaudry, 2007). This disruption is primarily owed to the change of how the customers value certain performance attributes. Figure 4 illustrates this change with the help of a radar chart. The left image shows the performance attribute mix as it was before the introduction of mp3 players. Sound quality was valued most by the customers since this was the main advantage of the CD over the cassette. Additionally, battery life and exchangeability of the medium were very important. With the introduction of the mp3 format, however, this changed dramatically. With a certain level of sound quality and rechargeable batteries taken for granted customers focused more on other attributes like capacity and portability/size. This ultimately led to the decline of the Discman demand.

This shift in the perceived value of a specific mix of attributes constitutes the shift in the perceived performance mix. It is very important for understanding disruptive technologies, as it is often the alternate performance *mix* that appeals to the customers and thus making the technology disruptive and not one single performance attribute. This can be seen very well in the example of the Discman: Despite the fact that the sound quality of the CD is vastly superior to the mp3 (Meyer, 2000), people stopped valuing the performance mix of the CD and turned to the performance mix provided by the mp3 format although inferior on some attributes.

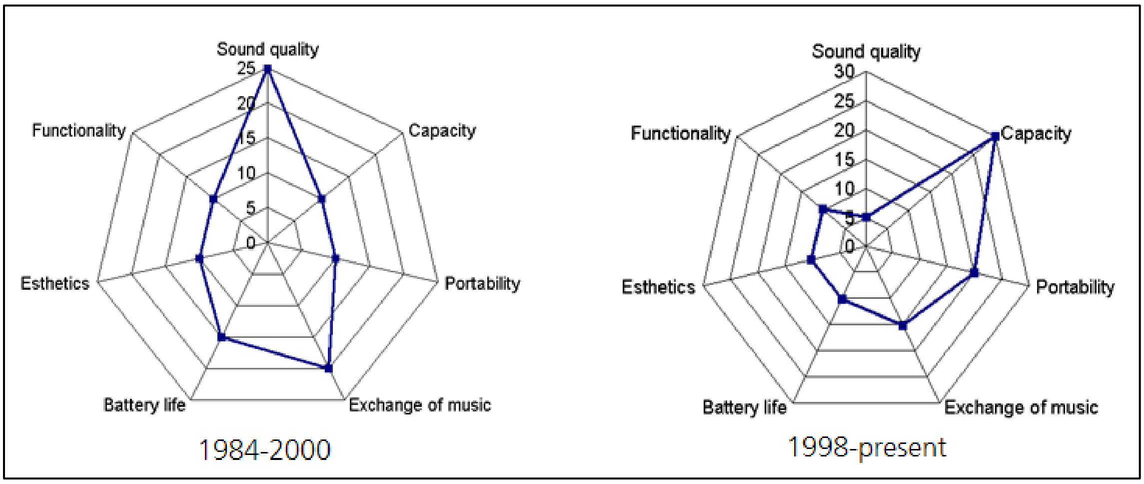

Figure 4. Perceived performance mix of portable music players in the Discman era. Data comes from personal experience with portable music players and is used to illustrate the concept of perceived performance mix. It is not empirically ascertained.

2.1.4 Disruptive Technologies

A technology that emerges out of a niche market and becomes so dominant that it disrupts the status quo of a market and often leads to incumbent companies being pushed out of the market is called *disruptive technology* (DT) (Christensen, 1997). The term was introduced in 1995 by Joseph L. Bower and Clayton M. Christensen. Disruptive technologies (DTs) are since popular object of research (also see Paap & Katz, 2004; Danneels, 2004; Sood & Tellis, 2005; Carayannopoulos, 2009) due to the threat that they pose to established, market-leading companies. Table 1 shows a few examples of disruptive technologies of the past 30 years.

Table 1

Examples of disruptive technologies

Dominant Technology (Incumbent)	Disruptive Technology (New entrant)	Disruptive Attribute	Period of Disruption
Workstations	Personal Computers	Cheap, for everyone	1980’s
5.25 inch disk drive	3.5 inch disk drive	Size, weight (laptops)	1980’s
Chemical Photography	Digital Photography	Capacity, development	2000’s
Compact Cassette	Compact Disc	Sound quality, capacity	1990’s
Discman	Mp3 players	Portability, capacity	2000 - 2005

Note. Data comes from various sources in magazines, books and online.

When a technology emerges, it is valued by the customers mainly on its most critical performance value (Adner, 2002). Over time, however, when the initial basic functionality or functional threshold is reached, the perceived performance mix of the technology starts to change. Disruptive technologies start out as inferior products serving a market niche. As technologies mature and the perceived performance mix changes, they start over-performing the dominant technology and appealing to the mainstream market. When this happens, the new technologies rapidly become the new standard and the old technologies along with their producers are being pushed out of the market. Because of the DTs’ initial technological inferiority and the differences in the perceived performance mix, established companies are often blind-sighted against the potential of the new technology. They believe that it can only serve a niche market and that the majority of their customers will not value its use. In fact, it is often their customers themselves that tell the incumbents that they do not value the new features (Christensen, 1997). Also supporting this is a quote from Tellis (2006, p. 34): “[…] *the disruption of incumbents - if* *and when it occurs - is due not to technological innovation per se but rather to incumbents' lack of vision of the mass market and an unwillingness to cannibalize assets to serve that market."*

From the above elaborated the following definition for DTs is derived:

> *A disruptive technology is a technology that disrupts the status quo of both the market position of the dominant technology and the competitive market layout by having an alternate perceived performance mix, which is valued more by the customer than the one of the dominant technology.*

2.2 Technology Evaluation Methods

Technology evaluation methods are used to justify decisions in technology investments. After evaluating technologies on their potential for future success, a forecast can be made. Because of this, forecasting methods are often used synonymously for technology evaluation methods. Forecasting methods use information from the past to forecast events in the future as depicted in Figure 5. This information can come in many forms like for example experience, performance data, intuition, trends and patterns. This process is based on the assumption that powerful feedback mechanisms in human society cause repetitive processes (i.e. future trends and events to occur in identifiable cycles and predictable patterns based on the past).

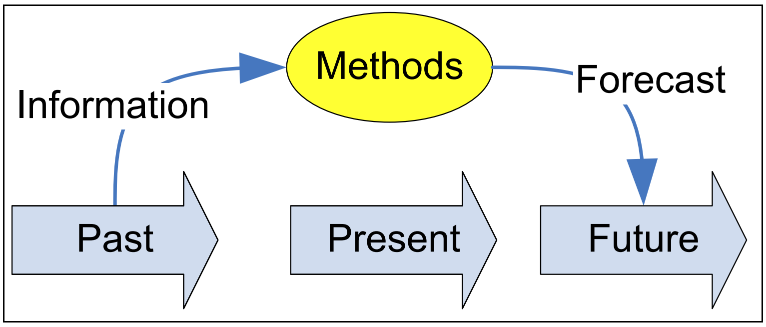

Figure 5. Operating principle of evaluation methods.

Accurate evaluation methods can contribute to the selection of the best alternatives leading to the best possible future state of the system. In here lays the forecasting dilemma: selecting a technology for development is essentially a self-fulfilling prophecy as it tries to measure if it gets developed in order to decide if it gets developed (Henshel, 1982). For example, a space technology that is identified as having a high potential of becoming a DST will be invested in and in this way become disruptive. In light of this, the term evaluation might be more appropriate because a technology concept will be evaluated on what its possible future can be and how beneficial this will be to the actors involved. Therefore, the term *evaluation methods* is used from now on.

Because of the clear benefit of evaluation, an extensive amount of literature has been written on this subject. Within this literature, different approaches of creating views on the future can be identified. In general, these views can be categorized as being either quantitative, qualitative or a combination of both. These different approaches are determined by separate sets of system thinking. System thinking is the process of trying to understand how elements interact and influence each other within a whole. According to Jackson (2000), there are two different ways of viewing systems: a hard systems approach and a soft systems approach.

Hard system analysis relies on quantitative methods and involves mostly simulations and mathematical techniques. The underlying view of this approach is that reality can be quantified and analyzed on quantitative variables. The benefit of this approach is that it is highly accurate. It can, however, take into account only simple elements and not complex measurements like opinions, culture and politics.

Soft system analysis relies on qualitative methods and is used for complex systems that cannot be easily quantified. It is especially useful for situations where complex human factors define interactions and relationships.

Vanston and Vanston (2004) developed a framework for strategic analysis based on how people see the future. These views are represented by five different kinds of people: Extrapolators, pattern analysts, goal analysts, counter-punchers and intuitors. As illustrated in Figure 6, these five views form different categories containing several methods of evaluation. They are depicted on an axis going through from quantitative to qualitative methods and are described and assessed on their advantages, disadvantages and applicability as evaluation methods for space technologies in the DLR study "Disruptive Technology Search for Space Application". Here, they are summarized in Section 3.2 of Chapter 3.

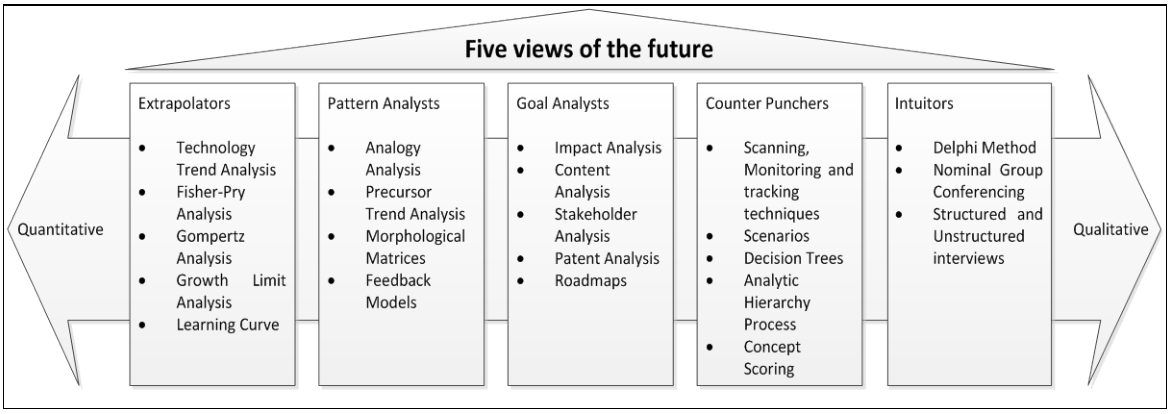

Figure 6. 'Five Views of the Future' strategic analysis framework. Adapted from "Testing the Tea Leaves: Evaluating the Validity of Forecasts," by J. H. Vanston and L. K. Vanston, 2004*, Research-Technology Management, Volume 47, Number 5*, p. 36

2.3 Space Sector Analysis

This section presents an analysis of the space sector and a presentation of its characteristic, its innovation dynamics and the different pathways of space technology development within the sector.

2.3.1 Space Sector Infrastructure

The space sector is a complex market which is highly influenced by governmental entities. Spread over the world, there are over 50 space agencies (for example NASA, ESA, JAXA and Roskosmos), more than 40 commercial operators and several institutional entities (for example NOAA, EUMETSAT, JME, and EC) that are procuring satellites and satellite related services. The key players of the space sector can generally be divided into two types; governmental institutions and commercial organizations (Tkatchova, 2011). These two types and their different sub-types are illustrated in Figure 7.

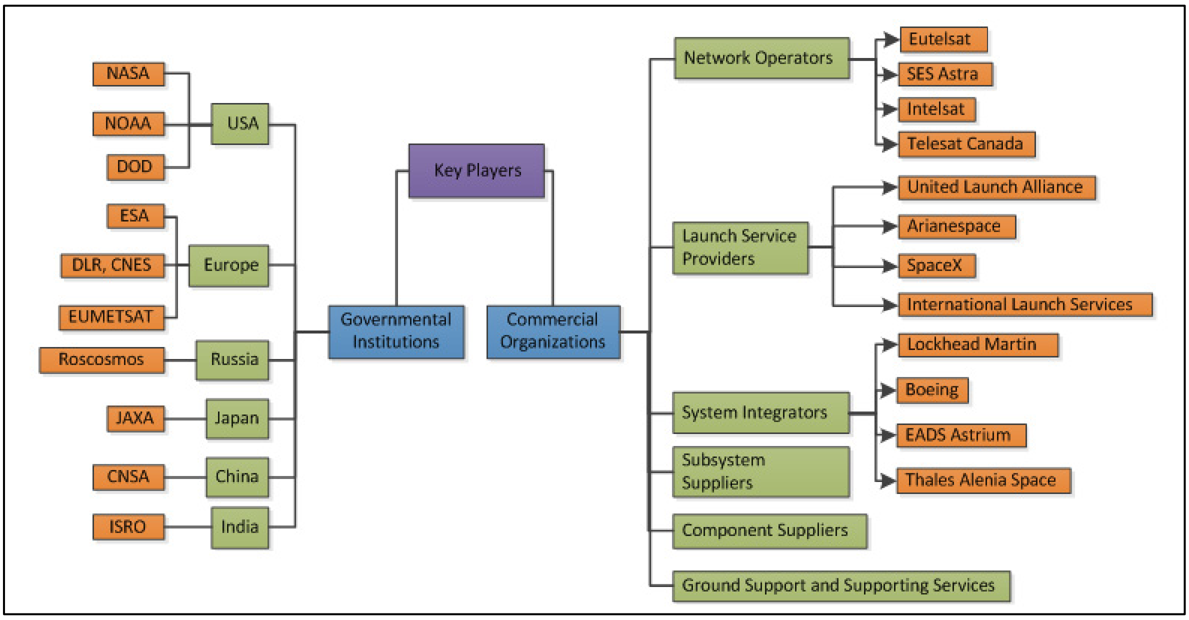

Figure 7. Key players of the space industry. Reprinted from "*Disruptive Space Technologies,*" by E. Veen, M. Gugliemi, D. A. Giannoulas, and D. Schubert, 2012, Manuscript submitted for publication. Reprinted with permission.

Funding for technology research and development generally flows from governmental institutions and network operators to the space sector industry. This funding has either military or civilian purposes (although many forms of dual-use technology development exist). Civilian missions can be categorized into commercial and scientific missions. For military missions, governmental institutions are the sole customers. For the civil purposes - both commercial and scientific missions - customers can either be governmental institutions or end-users/industry.

In general, the following market forms can be identified:

- Mass market: Multiple sellers that face multiple buyers
- Monopoly market: One seller that faces multiple buyers
- Monopsony market: One buyer that faces multiple sellers
- Oligopoly market: Few sellers that face multiple buyers
- Oligopsony market: Few buyers that face multiple sellers

The space sector has been characterized as a monopsony market, in which the government is the main investor in space related technologies (Szajnfarber & Weigel, 2007; Summerer 2011). This seems to hold up for civilian-science and military missions that rely mainly on governmental funding but not for civilian-commercial missions. Within the telecommunications and navigation market there are billions of potential customers, which make an oligopoly a more suitable characterization for this part of the market.

2.3.2 Space Technology Requirements

Within the space sector, research and development and the diffusion of technologies within their respective market are different when compared to terrestrial markets. Space is an especially harsh environment, which is not only hard to reach but also hard for technologies to operate in. This creates unique constraints in form of performance levels that greatly exceed those required for terrestrial technologies. These performance levels are determined by the following environmental constraints:

- High-energy radiation (both ionizing and electromagnetic)
- Extreme temperatures
- Large and frequent temperature variation
- Micrometeoroid and orbital debris impacts
- (Partial) vacuum
- High and low g-forces
- Limited opportunities for repairs or adjustments after launch

The constraints of the space environment have led to the following quality requirements for space technologies:

- High testing requirements – the multitude of environmental conditions are adding cost and complexity to the testing process
- High need of redundancy - in order to deal with unforeseen events and failures, a high degree of redundancy is required
- Strict quality assurance and quality control processes – to ensure functioning of technology under the right circumstances, strict quality control and assurance processes are required
- Long flight heritage – for vital missions, only components and sub-systems that have proven their capability to function in the actual space environment are chosen

Because of these high quality requirements, the following consequences for the market dynamics of the space sector can be observed:

- Low production volumes: Most of the new technology development is done from a mission pull perspective. This means that components are often designed to order. (Note: there has been an increasing trend towards the use of *commercially available off the shelf* (COTS) products in order to save costs).
- Reluctance to cannibalize: Space technologies often have a significant amount of equipment purchases, development costs, proprietary knowledge and human capital invested into them. These non-recurring costs lead to a reluctance of

incumbents to cannibalize existing technologies for new technology developments (Kamien & Schwartz, 1982).

- Political influence: Because of a relative low commercial drive for space exploration, the space sector, especially the scientific domain, remains highly funded and controlled by governmental entities. This makes technology investment decisions highly subject to policy changes caused (in part) by political changeovers.

2.3.3 Space Technology Development

The space sector has always been regarded as a high-tech sector that boosts science in a range of scientific fields such as meteorology, astronomy, geography, geodesy and medicine. Due to research & development efforts and the therefrom resulting innovations, the technological capabilities of the space sector are steadily increasing. Because of budget constraints, however, only a small portion of the inventions and technology concepts available can be researched and eventually developed. These technology concepts are mostly *incremental innovations* upon the dominant technology and provide small improvements in the performance of a technology. According to Summerer (2009) this is partly caused by a risk-adverse culture in the space sector that leaves only a small margin of freedom for testing innovations in subsystems that are not imperative for achieving mission success.

Incremental innovations are the opposite of *radical innovations* (Henderson & Clark, 1990). Radical or breakthrough innovations are innovations that cause a technology domain to make a leap in its performance evolution (Veryzer, 1998). Radical innovations are considered as totally new technologies within a technology domain because of their fundamental differences compared to the previous dominant technology. To further clarify this, Leifer et al. (2000) describe an incremental innovation as the exploitation of a technology while a radical innovation is the exploration of a new technology. In general, radical innovations have the potential to be more beneficial to the space sector than incremental innovations.

In the space sector, technology development can come from a *technology push* or through a *demand pull*. Technology push means, that a technology is developed and produced before an actual need for it arises while a demand (or market) pull is characterized by the identification of a need for a specific technology and the subsequent development of it (Martin, 1994). When looking at the technology push and demand pull models and drawing a parallel to technology development in the space sector, basic research can be identified as the technology push factor while technology developed for specific missions can be identified as the demand pull (Summerer, 2011). When looking for disruptive technologies, technology push areas are of particular interest because it is them that mostly result in breakthrough technologies while pull investments result more in incremental innovations (Nemet, 2009; Carayannis & Roy, 2000).

3 DLR Study Findings

This chapter describes the findings and the steps of the method development process already performed by the DLR study Disruptive Technology Search for Space Application. The outcome of these steps is considered given knowledge for the purpose of this paper and thus serves as additional theoretical background for the development of the evaluation method.

3.1 Disruptive Space Technologies

In order to develop an evaluation method for disruptive technologies in the space sector, the specifics of this sector have to be considered and the theory of disruptive technologies has to be reviewed in respect to its applicability on space technologies. Section 2.3 elaborated on the space sector infrastructure, requirements that exist specifically for space technologies and the different pathways of space technology development within this sector. Through insights gained in this section it has become clear that the space sector is sufficiently different from terrestrial (mass) markets and that a reassessment of the theory of DTs and the creation of a new theory on disruptive technologies within the space sector is necessary.

3.1.1 Disruptive Technologies in the Space Sector

To better understand the impact, evolution and manifestation of disruptive technologies and the path they take in replacing existing technologies, several technologies that have been disruptive for the space sector in the past have been investigated.

Although some of the characteristics of DTs are the same in conventional markets as they are in the space sector (for example they both start developing in a niche market before encroaching on the market of the dominant technology), a historical analysis of five technology concepts performed in the study DLR study Disruptive Technology Search for Space Application has shown a number of important differences between the DT theory as described by Christensen and the way disruptive technologies disrupt the status quo of the space sector. The major difference seems to be that with the disruption of technologies no major shifts were observable in the competitive market layout. This is most likely caused by a combination of the following factors, which also mark the biggest differences between technologies in the space sector and technologies in conventional markets:

- Development time: The development of a space technology takes a long time and therefore the response time of the incumbents to the new technology is high.

They can either choose to start a development process of their own (if the development time permits it) or take over the company marketing the new technology.

- Risk: The long development time and the high reliability requirements of a space technology cause the risk of an investment to be very high. This constitutes a large barrier for new startup companies as it makes finding investors very difficult.
- Initial investments: Space technologies often have a significant amount of equipment purchases, development costs, proprietary knowledge and human capital invested into them. These non-recurring costs lead to a reluctance of incumbents to cannibalize existing technologies for new technology developments.
- Flight heritage: A dominant space technology already has a long flight heritage. Flight heritage means that the technology has already been extensively tested in space, which increases reliability and decreases risk. A new space technology candidate has to be a significant improvement to the dominant technology to justify the increase in risk and decrease in reliability.
- Market characteristics: The space sector is a complex market that is highly influenced by governmental entities. Development and usage of a technology is often linked to political motives and/or social aspects.

3.1.2 Definition of Disruptive Space Technologies

Due to the reasons mentioned in the previous subsection, DTs, as described in business literature, are not the same in the space sector. Therefore, in the course of this work, an adjusted theory is developed for the space sector called: *disruptive space technologies* (DSTs). When analyzing the innovation literature and the theory of DTs, a resemblance can be found between radical innovations and DTs. Both are exploitations of new technologies and replace dominant technologies. Additionally, they both offer a higher performance in the perceived performance mix. The key difference between radical innovations and disruptive space technologies is that DSTs do this in an unexpected way. In other words: they over-perform the dominant technology on an alternate (changed) perceived performance mix. The key characteristics of DSTs can be summarized as follows:

- DSTs are explorations of new technologies. They represent a significant improvement in performance along a discontinued perceived performance mix (of a part) of the market. Therefore, a technology replacement by a DST can be characterized as an unexpected event in the space sector.

- In the space sector, a technology can still be disruptive even if it does not disrupt the competitive market layout by pushing the dominant technology producers/marketers out of the market. A technology replacement in an unexpected manner can be enough to label a space technology as disruptive. This means that DSTs focus on the disruption of technologies rather than the disruption of markets. However, disruption is also caused by market factors (perceived performance mix) and not solely by technological factors (performance).
- DSTs are product innovations according to the 4P paradigm (product, process, paradigm and position innovation) of Francis and Bessant (2005). Although a technology can be either a product or a process (as defined in Subsection 2.1.1) this research and the theory of DSTs only focuses on product innovations.

From the above mentioned the following definition of DSTs is derived:

A disruptive space technology is an emerging technology that disrupts the status quo of the space sector by replacing the dominant technology and marking a radical improvement in the perceived performance mix.

A brief note on the terminology:

Soon after the emergence of the term disruptive technologies, Christensen revised it to *disruptive innovations*. This was done for two reasons. For one, innovation is a broader term and includes paradigm and position innovation (see Subsection 0), in contradistinction to the term technology, which is usually a product or process innovation. The other reason was that a technology itself is never disruptive, only its successful application is. As already argued in Subsection 0, the successful application of a new technology is defined as innovation thus making the term 'disruptive innovation' in general far more accurate (Christensen & Raynor, 2003). Since, however, the focus of this research is solely on product innovation it is felt, that the term disruptive space *technology* better reflects the subject of this research and is hence deliberately chosen.

3.2 Evaluation Method Analysis

This section presents the summary of an in-detail analysis of the evaluation methods with respect to the space sector as presented in the "Five Views of the Future" framework by Vanston and Vanston (2004). The detailed presentation of the analysis would go beyond the scope of this research and thus, only the results are shown here. In the following, the different categories of the framework are depicted, their methods mentioned and examined on DST relevance.

3.2.1 Extrapolating Methods

Extrapolating methods are based on the view that the future will be a logical extension of the past. Complex forces will drive the future in a predictable manner and that can be used for creating forecasts. Based on analyzing trends of the past, forecasts can be made by extrapolating past data according to mathematical principles (Vanston & Vanston, 2004). The methods that follow this hard view on systems are highly quantitative in nature. They are: *Technology Trend Analysis* (Wilson, 1987), *Fisher-Pry Analysis* (Fisher & Pry, 1971), *Gompertz Analysis* (Vanston & Vanston, 1996), *Growth Limit Analysis* (Martino, 1993) and *Learning Curves* (Porter, Roper, Mason, Rossini, & Banks, 1991).

Extrapolating methods cannot be used for forecasting DSTs because DSTs do not compete with dominant technologies on their primary performance dimension. This makes the extrapolation of a trend of the past in the performance of the primary performance dimension useless because one characteristic of DSTs is that they will not follow this trend. Additionally, for extrapolation, a forecaster would need many accurate data points over a relatively long period of time in order to extrapolate the trend. Such long periods are usually not available in the space sector due to the irregular use of space technologies. That makes identifying trends very complicated and rarely accurate.

3.2.2 Pattern Analysis

Pattern analysts believe that the future will reproduce a replication of past events. This view of reality has led to a method of identifying and analyzing analogous situations of the subject technology and applying the found patterns to predict its future development (Vanston, 2003). The adoption of color television, for example, closely followed that of black-and-white television and that, in turn, followed the pattern of radio adoption. Thus, one might reasonably forecast the pattern for future adoption of high-definition television by examining the pattern of past adoption of color television. However, it is quite possible to choose an invalid analogy and, in any case, future developments never exactly replicate past analogies. This field differentiates itself from extrapolators in a way that it is broader by focusing on more than one single performance dimension or technology replacement. Pattern Analysis methods are: *Analogy Analysis* (Porter et al., 1991), *Precursor Trend Analysis* (Martino, 1993), *Morphological Matrices* (Bright, 1978) and *Feedback Models* (Bright, 1978).

Pattern Analysis is in some degree applicable for forecasting DSTs. Especially Precursor Analysis can be applied in determining the timeframe of the dominant technology's disruption by the DST. This might, however, be difficult to determine due to the low frequency in which space technologies are used and the inaccuracy of past data (same reason Analogy Analysis is not applicable).

3.2.3 Goal Analysis

Goal analysts believe that the future will be defined by the beliefs and actions of various individuals, organizations and institutions. The future is therefore not determined and is susceptible to alteration by one or several of these entities. Because of this, a forecast can be made using the stated and implied goals of the various decision makers and trendsetters (Vanston, 2003). In the case of space industry, a good example would be the European space policy and the included technology objectives, which serve as a strategy for the technology development in Europe. Examples of goal analysts are: *Impact Analysis* (Vanston, 1988), *Content Analysis* (Kroppendorf, 1981), *Stakeholder Analysis* (Stevensen, 1998) and *Patent Analysis* (Porter et al., 1991).

In general, Goal Analysis is well applicable for forecasting DSTs because it analyzes markets instead of focusing on the technology. Impact Analysis has little predictive value as it merely describes the impact of an innovation if it were to be successful and is therefore unusable. Content Analysis can be very helpful in the future as this technique develops but is not useable yet because it cannot follow trends of specific technologies. Stakeholder Analysis is usable as the stakeholders for technology development in the European space sector are both pushers and pullers. This, however, can be more of a tool that helps with the development rather than for the evaluation of a technology. Patent Analysis examines the number and type of patents approved or rejected over a specific period of time. It is not a strong indicator for DSTs as they are mostly unexpected by the main market and therefore the patents involving a potential DST will be non-distinctive and in very small numbers.

3.2.4 Counter-Punching

Counter-punchers believe that forces shaping the future are highly complex and therefore future events are essentially unpredictable. They propose that the best way of handling the future is by identifying a wide range of possible trends and events by monitoring changes in technical and market environments. The way to cope with changes from an unpredictable future is by maintaining a high degree of flexibility in the technology planning process (Vanston & Vanston, 2004). The techniques and methods are: *Scanning,* *Monitoring and Tracking* (Vanston, 1988; Bright, 1978), *Alternate Scenarios* (Vanston, 1988; Bright, 1978) and *Decision Analysis* (Porter et al., 1991). Decision Analysis includes the *Analytic Hierarchy Process* (Saaty, 1980) and *Concept Scoring* (Ulrich & Eppinger, 2000).

In general, Counter-Punching techniques are well applicable for forecasting DSTs. Especially Decision Analysis techniques are very promising. The Analytic Hierarchy Process (AHP) can be used for multi-criteria analysis since it involves the reduction of complex decision such as the ones that have to be made for the evaluation of potential DSTs. The Concept Scoring method can be used to provide a scoring matrix for ratings on different criteria weighted accordingly.

3.2.5 Intuitive Methods

Intuitors believe that the future will be realized through a complex mixture of trends, random occurrences and the actions of individuals and institutions. Because of this complexity, they believe that no technique can provide an accurate forecast of the future. Therefore, they usually rely on the subconscious information processing capability of the human brain and use this to provide useful insights about the future (Vanston & Vanston, 2004). They do this by feeding the brain with information and allow intuition and experience (tacit knowledge) of experts to make judgments on the likelihood of a future event. Methods are: *The Delphi method* (Linstone & Turoff, 1975), *Nominal Group Conferencing* (Vanston, 1988) and *Structured* and *Unstructured interviews* (Vanston, 1988).

Intuitive methods are very well applicable for forecasting DSTs. Especially the Delphi technique is ideal for this since it involves a group of experts that has to reach a consensus on a question. Additionally, the Delphi method benefits from decreased bias through anonymity and allows communication over long distances. The later makes the Delphi technique very interesting for the space sector as experts are often located all over the world. This also makes Nominal Group Conferencing and the interview techniques less appealing as traveling for interviews might be highly time-consuming and costly.

3.2.6 Conclusions

Table 2 offers an overview of the evaluation methods discussed with the required information input, type of forecast, applicability for forecasting DSTs and required effort. As can be seen, the Scanning Monitoring and Tracking techniques (SMTs), Concept Scoring, the AHP and the Delphi method are ranked highest in their applicability to DSTs and seem to be most promising.

Table 2

Evaluation methods overview

Method	Information input	Type of forecast	Applicability to DST *	Effort **
Extrapolating Methods				
Technology Trend Analysis	Performance data	Technology performance trend	2	3
Fisher-Pry Analysis	Adoption data	S-Curve graph	2	4
Gompertz Analysis	Adoption data	S-Curve graph	2	4
Growth Limit Analysis	Performance data	S-Curve graph	2	3
Learning Curve	Cost data/performance data	Cost graph	3	3
Pattern Analysis				
Analogy Analysis	Technology analogy data	Adoption pattern	2	2
Precursor Trend Analysis	Adoption times	Adoption time	2	2
Feedback Models	Environment factors	Relationship factors	1	2
Goal Analysis				
Impact Analysis	Brainstorm session	Unforeseen events	2	3
Content Analysis	Trends in media attention	Future interest	3	5
Stakeholder Analysis	Stakeholder information	Influence by stakeholders	3	4
Patent Analysis	Patent trends	Future scientific interest	3	3
Counter-Punching				
Scanning, Monitoring and Tracking techniques	Past and real-time performance data	Continuous forecast	5	1
Alternate Scenarios	Various sources	Scenarios Forecast	2	2
Analytic Hierarchy Process	Expert opinions	AHP model	5	2
Concept Scoring	Expert opinions	Potential rating	4	4
Intuitive Methods				
Delphi method	Expert opinions	Expert ratings	5	2
Nominal Group Conferencing	Expert opinions in brainstorming form	Expert ratings	3	2
Structured and Unstructured interviews	Interviews	Expert ratings	3	3

* 1=Not applicable, 2=Somewhat applicable, 3=Reasonably applicable, 4=Well applicable, 5=Very well applicable
** 1=Heavy, 2=Substantial, 3=Reasonable, 4=Little, 5=Very little

3.3 Search Strategy Development

In order to explore the different technology concepts available and to create a database of potential DST candidates that will serve as a source for the DST evaluation method, a broad technology scan is performed. The first step of this technology scan is the development of the search strategy where a suitable concept for identifying DST candidates is devised. Since the development and application of the search strategy is not object of this study, the process is only summarized and not elaborated on in detail. The created database is used as a source of data in in the case study presented in Chapter 6.

In order to form a search strategy, a viable search method is selected and search criteria are defined. This is done by analyzing existing search methods with respect to space sector specifics and hence determining their applicability for a DST candidate search. The search methods considered here are the following: The *Lead User method* (von Hippel, 1988), the *Document Influence Model* (Gerrish & Blei, 2010), the *Quid algorithm* (Giles, 2011), patent search methods (Hunt, Nguyen, & Rodgers, 2007) and survey-based data collection methods (Franklin & Walker, 2010). Table 3 shows the key features of each method along with its advantages and disadvantages.

Table 3

Search methods overview

	Key Features	Advantages	Disadvantages
Lead User method	Identifies needs of lead users to detect future technology trends	Can identify technology needs and therefore opportunities for disruptiveness	Not usable for small markets like the space market
Document Influence Model	Searches in a collection of articles for texts that influence the language of following texts	Can detect most influential documents in a collection	Needs a lot of articles about technologies and detects DST´s too late
The Quid algorithm	Uses many different information sources and its own algorithm	Can detect connections between different fields and disciplines	The algorithm is not published and it is in the beta test phase
Patent search methods	Searches in databases of over 70 million patents	Huge up to date database	Lack of a customized search program for DSTs / very time intensive
Survey-based data collection methods	Can detect spin-in technologies by inquiring individuals of other markets	Collection ideas from many different individuals and working fields	Results depend on who is asked / willingness to participate is often low

Survey-based data collection methods are found to be the most viable for a potential DST search and thus incorporated into the search strategy in form of an internet-based expert survey. In order to broaden the scope of the search, the strategy is complemented with a desk research and a technology database search.

4 Research Methodology

This chapter elaborates on the methodology of the evaluation method design. Section 4.1 describes the process of the evaluation method selection. After the method is chosen the criteria, which the technologies will be evaluated upon, are selected. A number of different approaches are examined and the appropriate criteria selected. This is presented in Section 4.2. The methodology of the subsequent selection of a suitable weighing method is described in Section 4.3.

4.1 Evaluation Method Selection

The evaluation method is selected on the basis of the evaluation method analysis presented in Section 3.2. The most applicable methods for DST evaluation (see Table 2) are examined on their ability to fulfill certain requirements. These requirements are derived from the general needs of the space sector as presented in the space sector analysis (compare Section 2.3), the specific needs arising from the theory on disruptive space technologies and the needs that have become evident during the course of this work. They are the following:

- Quality and reliability of data: The selected method must be able to produce reliable data with a high quality to ensure the highest possible precision of the evaluation process.
- Reliability of method: The selected method must be a well proven method with little or no doubt about its effectiveness, its reliability to produce accurate results and its ability to meet the difficulty of evaluating and forecasting future technology concepts
- Need for a pre-selection: The technology scan already performed has made evident that the number of technology concepts with innovation potential from both in- and outside of the space sector is very large. However, the technology concepts that actually have the potential to be disruptive for the space sector are far less. The ability to filter out the technology concepts that are too immature, do not have a sufficient disruptive potential or are outside of the search scope is an essential element of the method.
- Time allocation/work effort: The selected method must represent an amount of work effort that does not exceed a certain limit. In order to evaluate existing technology concepts and have results within a reasonable timeframe, time allocation and work effort of the method must be such, that it is performable inside a six to twelve month period.

A combination of methods that fulfill the above-listed requirements to the highest extend is chosen. The following four methods have scored highest on their applicability for DST evaluation and are examined on their ability to comply with the requirements.

4.1.1 The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a method for multi-criteria decision analysis (Saaty, 1980). It involves the reduction of complex decisions to a series of pair-wise comparisons and then then synthesizing the results. Decision-makers arrive at the best decision with a clear rationale. Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another. In making the comparisons, the decision makers can use concrete data about the elements, or they can use their judgments about the elements' relative meaning and importance. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations. This makes the technique semi-qualitative. An example of the AHP is shown in Figure 8.

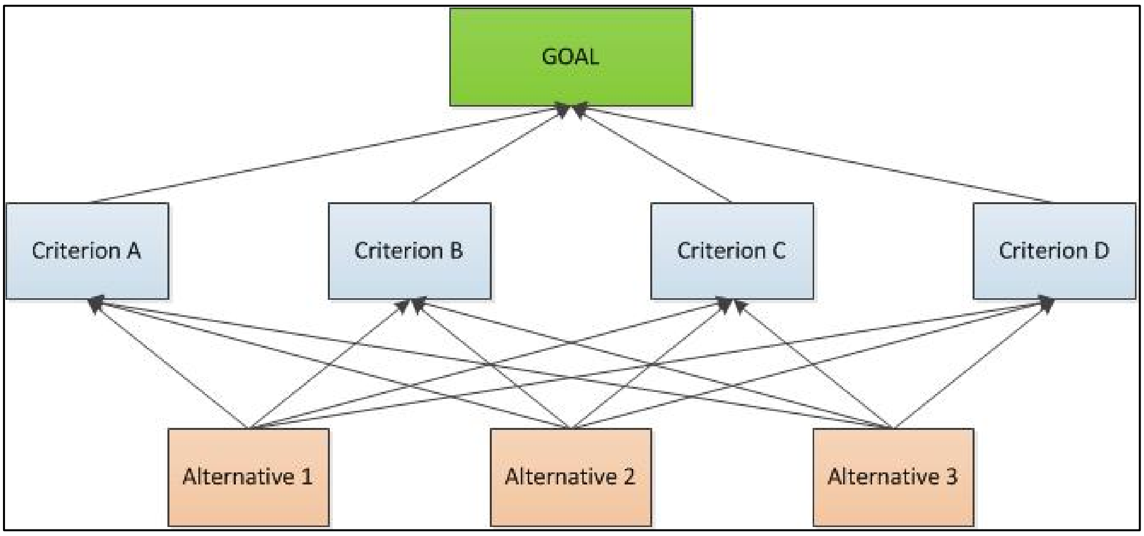

Figure 8. Example of the AHP process. A decision (goal) is split unto sub-decisions (criteria). Each alternative is evaluated indiviadually on each criterion, which then in turn are combined to form the goal.

4.1.2 The Delphi Method

The Delphi method is a widely used and accepted technique for achieving convergence of opinion and gathering data from respondents within their domain of expertise (Hsu & Sandford, 2007). Its far-reaching field of application includes two particular uses that represent the main goals of Delphi surveys and their benefits: The first is to provide judgmental data in areas, where hard data is either unavailable or too costly to obtain and can be used as input data in studies. The second is the use of the Delphi technique in the process of supplying decision makers with reliable expert opinions (Helmer, 1975). In extension, both of these applications are often used as forecasting tools (Rowe & Wright, 1999) or as part of technology forecasting methods.

The Delphi method has its origins in US American defense research. Sponsored by the United States Air Force and developed by the RAND Corporation in the mid-1950s mainly by Norman Dalkey and Olaf Helmer (1963), it had the purpose of estimating the effects of a massive nuclear attack on the United States (Helmer, 1975). Even if all the factors could have been assessed, which is considered unlikely, a statistical analysis of this scale would not have been possible with the computers of that time. Thus, taking into account the opinion of experts was the only feasible solution for a prediction of that kind and delivered the original justification for the first Delphi study (Linstone & Turoff, 1975).

Since its invention, the Delphi Method has come a long way. While used mainly as a technology forecasting tool in the mid-1960s (Helmer, 1975), it has evolved to arguably one of the most popular incentive evaluation methods today with the number of studies being conducted rising in only a decade from a three digit count in the late 1960s to a four digit number in the 1970s (Linstone & Turoff, 1975). Since then, the field of application has been extensively diversified and its characteristics have been expanded in practice and in literature (Häder & Häder, 1998).

A general description of the Delphi method given by Wechsler (1978) reads as follows:

> It is a survey which is steered by a monitor group, comprises several rounds of a group of experts, who are anonymous among each other and for whose subjective-intuitive prognoses a consensus is aimed at. After each survey round, a standard feedback about the statistical group judgment calculated from median and quartiles of single prognoses is given and if possible, the arguments and counterarguments of the extreme answers are fed back. (pp. 23f.)

According to Linstone and Turoff (1975), there are two basic forms of the Delphi process. The first is the "paper-and-pencil version" where a small monitor team develops a questionnaire, which is then sent to the participants of the survey. Upon return of the questionnaire, a new questionnaire is created based on the answers on the original one. The next iteration round informs the participants of the results of the first round and gives them the opportunity to re-evaluate their opinions taking into consideration the knowledge of the entire group. This form is called the "conventional Delphi".

The second form called "Delphi conference" replaces the monitor team with a computer programmed to carry out the compilation of the group results. This approach has the advantage that the delay between the iteration rounds is eliminated and the process is concluded much faster. It requires however, that the characteristics of the communication are well defined before the Delphi is undertaken since they cannot be later adjusted according to the group responses (Linstone & Turoff, 1975).

One of the main advantages of the Delphi method is that it constitutes a process of gaining consensus from a group of experts while maintaining their anonymity to decrease bias. According to Dalkey (1969), bias can come from communication that occurs in a group process and that deals with individual interests rather than focusing on solving the problem. Furthermore, it can come from the effect that dominant individuals have over others in terms of opinion forming. Without the presence of others, respondents can revise their answers without having to fear social implications. Another advantage of this method is the low cost in comparison to a high output. This is well illustrated by Jillson (1975) in the example of a policy Delphi on drug abuse, a special form of the Delphi method (see Turoff, 1970). The ability to conduct a Delphi with respondents spread over a wide geographic area is another advantage of the Delphi method (Linstone & Turoff, 1975).

Time requirements can be seen as one of the biggest drawbacks of the Delphi method. The conclusion of each iteration round can only be conducted once all the participants have sent in their answers. As a consequence of this delay, participants can lose interest and drop out the study. Lindstone and Turoff (1975) regard the following as the most common reasons for a Delphi failure:

- Imposing monitor views and preconceptions of a problem upon the respondent group
- Assuming that Delphi can be a surrogate for all other human communications
- Poor techniques of summarizing and presenting the group response
- Ignoring and not exploring disagreements
- Underestimating the demanding nature of a Delphi and the fact that respondents should he recognized as consultants and properly compensated for their time

The field of application for the Delphi method is vast. As previously stated, the Delphi method can be applied to virtually any circumstance and endeavor where data is not accurately known or available. A few of them, developed as early as 1975 are given exemplarily (Linstone & Turoff):

- Gathering current and historical data not accurately known or available

- Examining the significance of historical events
- Evaluating possible budget allocations
- Exploring urban and regional planning options
- Planning university campus and curriculum development
- Putting together the structure of a model
- Delineating the pros and cons associated with potential policy options
- Developing causal relationships in complex economic or social phenomena
- Distinguishing and clarifying real and perceived human motivations
- Exposing priorities of personal values, social goals

Fundamental criticism as to whether or not the Delphi principle works cannot be found in modern literature any more. The virtually proven reliability of the method and the vast number of applications it has successfully undertaken can be seen as probable reasons for that (Häder & Häder, 1998). It is, however, the massive criticism that the Delphi method has undergone since its invention that allows it to be the dependable and consistent evaluation tool as we know it today. Ranging from skepticism to total rejection, the criticism of the method has evoked a bulk of methodical research and controversy in literature that has influenced the method in a positive way (Häder & Häder, 1998).

4.1.3 Concept Scoring

The concept scoring matrix incorporates a ranking of concepts through a structured method (Ulrich & Eppinger, 2000). It involves the selection of a concept for investment by taking the following steps:

1. Prepare a selection matrix
2. Rate concepts
3. Rank concepts
4. Combine and improve concepts
5. Select one or more concepts
6. Reflect on the results of the process

An example of the matrix used in this method is illustrated in Table 4. It shows a scoring of different concepts. Each concept is scored on three different criteria that are again divided into sub-criteria. The method uses a weighted factor to adjust the level importance of each criterion and sub-criterion. The allocation of the weighted factor per criterion differs with every evaluated concept and has to be determined by the evaluator. Most criteria result in numbers that can be compared with each other.

Table 4

Example of a concept scoring matrix

		CONCEPT 1		CONCEPT 2		CONCEPT 3		CONCEPT 4	
Criteria	Wheight	Rating	Wheighted Score	Rating	Wheighted Score	Rating	Wheighted Score	Rating	Wheighted Score
CRITERION A	25%								
Sub-criterion A1	5%	7	0,35	10	0,5	8	0,4	7	0,35
Sub-criterion A2	20%	4	0,8	5	1	9	1,8	4	0,8
CRITERION B	65%								
Sub-criterion B1	30%	3	0,9	6	1,8	7	2,1	3	0,9
Sub-criterion B2	15%	4	0,6	6	0,9	4	0,6	9	1,35
Sub-criterion B3	20%	7	1,4	5	1	5	1	4	0,8
CRITERION C	10%								
Sub-criterion C1	5%	8	0,4	1	0,05	8	0,4	8	0,4
Sub-criterion C2	5%	3	0,15	8	0,4	6	0,3	4	0,2
Total Score			4,6		5,65		6,6		4,8
Rank		4th		2nd		1st		3rd	

4.1.4 Scanning Monitoring and Tracking Techniques

Scanning, Monitoring and Tracking techniques are based on the principle that for most new technologies a considerable amount of time is required from invention to innovation. When considering this, an alert organization can take advantages of this lag-time through the techniques discussed before. While all techniques involve the analysis of technology development within a sector, they do differ in purpose, methodology, and degree of focus.

Scanning techniques involve a broad scan of a sector in order to detect promising technologies and different trends. Monitoring follows the trend in broad fields and markets. Finally, tracking involves the continuous observation of developments in a specified area (specific technologies, market developments etc.). Results of these techniques can be highly quantitative to basically qualitative, depending on the technique used. These techniques require a high amount of effort over a continuous period but provide a real-time protection against disruptive effects within a market.

4.2 Criteria Selection

After selecting a combination of methods that are applicable for evaluating space technologies and fulfill the listed requirements, the different criteria, on which the technologies will be evaluated upon, are determined. Criteria are different factors that determine the overall value of a technology. Business management literature has already spawned several journal papers and books on evaluating, forecasting and predicting disruptive technologies. These sources are analyzed in order to determine if their view on DTs fits with the theory of DSTs, what their evaluation methodology is and if the methodology can be applied for the evaluation of DST candidates. The different research groups and their DT prediction methods that are reviewed are:

- Seeing What's Next methodology (Christensen, Anthony, & Roth, 2004)
- SAILS methodology (Vojak & Chambers, 2004)
- Linear Reservation Space methodology (Schmidt & Druehl, 2008)
- Value Trajectory methodology (Adner, 2002)
- Scenario Planning methodology (Drew, 2006)
- Measuring Disruptiveness methodology (Govindarajan & Kopalle, 2005)
- Propositional Framework methodology (Sainio & Puumalainen, 2007)

From these sources, criteria that seem applicable for the evaluation of DSTs are derived. The specifics of the space sector as described in Section 2.3 as well as the theory on disruptive space technologies are taken into account. The different criteria are then sorted into the four categories of the macro-environmental domains of the *STEP* analysis. STEP is an acronym that stands for *Social, Technical, Economic and Political* and is also sometimes referred to as PEST or SEPT (Peng & Nunes, 2007). It defines the four factors that influence the business environment and are of importance in decision making and in the creation of a business strategy (Fahey & Narayanan, 1986). Here, the STEP analysis serves as a framework for the categorization of the criteria:

- Social: The factors within the social domain influence technology diffusion within the space sector by influencing the demand of the technology. This means that if the public perception of a technology changes, the investment decision makers will be influenced in their technology development decision. The social domain is fairly weak compared to the other domains but might nonetheless provide an indicator to disruptiveness.
- Technical: The technical domain measures factors like performance and impacts on other systems. It is the most important evaluation segment because the over-performance of a technology is essential to disruption. However, it is important to note, that the technology does not need to be obviously better than the state-of-the-art as this would merely identify a sustaining innovation. Over-performance is rather to be understood as the performance that a group of customers of the technology finds more suited to its needs than the performance of the state-of-the-art technology. The performance of a technology in the technical domain is

determined solely by its performance on technical attributes such as efficiency, reliability, lifetime, mass etc.

- Economic: The economic factor measures the monetary aspects of space technologies. DSTs are technologies that make operations simpler, cheaper, more flexible, and/or more responsive compared to the dominant technology. Economic aspects are of high importance in identifying space technologies. A rating on economic factors should encompass whether or not the technology concept provides significant economic benefits to its users.
- Political: In the space sector analysis it is concluded that technology development is highly influenced by governments and thus by political decisions. Because of this, the political domain has a fairly strong influence on the development of technologies.

4.3 Criteria Weighting and Scoring

As already made evident in the description of the domains above, not every domain can be treated equally regarding the importance of it and its influence on the evaluation result. It is also reasonable to assume that the different criteria inside the respective domains have an unequal importance in respect to their contribution to the overall evaluation of a technology. Therefore, a weighting method is introduced in order to place the correct value of importance on each domain and on each criterion. Since the Analytic Hierarchy Process involves the creating of sub-problems and has, furthermore, already been identified as a valid method for evaluating DSTs, it is used to determine the importance of the different domains. This is done by following a method called pairwise comparison. These comparisons are transformed into so called priorities, i.e. weight factors that are used for the calculation of the weighted score for each technology. The factors are also checked on their consistency (Teknomo, 2006). The process is explained below on the example of the 4 domains of the STEP framework.

As a first step, the criteria are compared inside a priority matrix to receive relative weights to each other, but only in pairs. The values that are used in the priority matrix can be seen in Table 5. These values apply on all pairwise comparisons done in the course of this work.

Table 5

The fundamental scale for pairwise comparisons

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment moderately favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

With these values a comparison matrix is set up, which is then used to calculate the priorities (i.e. the actual weights) of the AHP process.

Table 6

Pairwise comparison of the AHP criteria for the 4 domains of the STEP framework

Social	1	Technical	9	Technical factors are much more important than social factors because they determine if a DST is better than the state of the art. Weight: 9
Social	1	Economic	5	Economic factors are more important than social factors because a decrease in any form of costs makes the technology more interesting for development. Weight: 5
Social	1	Political	4	Since political factors are highly important within the space sector, it has a moderate increased performance over social factors. Weight: 4
Technical	4	Economic	1	Technical factors are more important than economic factors because a DST might also be a high-end encroachment. Weight: 4
Technical	6	Political	1	Technical factors are strongly more important than political factors because they determine the value of a technology. Weight: 6
Economic	3	Political	1	Economic factors are slightly more important than political factors because an important factor for political decisions are economic factors Weight: 3

Table 6 shows the comparisons and the respective scores, the comparison matrix is depicted in Table 7.

Table 7

Comparison matrix for priority calculations

	Technical	Political	Economic	Social
Technical	1	6	4	9
Political	1/6	1	1/3	4
Economic	1/4	3	1	5
Social	1/9	1/4	1/5	1

The priorities for the individual criteria are then calculated via the eigenvalues and eigenvectors. They are the components of the normalized eigenvector of the priorities matrix:

$$(\overline{\mathbf{A}}\mathrm{x} - \lambda\overline{\mathbf{E}}) = 0,$$

where *A* denotes the priorities matrix, *E* the unity matrix and *x* the solution vector, whereas λ signifies the eigenvalue. With the above given matrix, the equation becomes:

$$\begin{pmatrix} 1-\lambda & 6 & 4 & 9 \\ 1/6 & 1-\lambda & 1/3 & 4 \\ 1/4 & 3 & 1-\lambda & 5 \\ 1/9 & 1/4 & 1/5 & 1-\lambda \end{pmatrix} = 0$$

From this, the characteristic polynomial is formulated and the solutions λ are determined as eigenvalues.

As the values for each criterion are selected more or less arbitrarily on the evaluators' discretion, the result needs to be checked on its consistency. This is achieved by a comparison with a random matrix, i.e. a Random Consistency Index (RI) (Teknomo, 2006). For this, a consistency index *CI* for the given matrix is calculated via the formula:

$$CI = \frac{k-n}{n-1},$$

where *n* is the number of dimensions of the comparison matrix and *k* the eigenvalue.

For the scoring of the criteria, different scales such as a ration scale *of zero to ten*, the *Likert scale* (Lehmann, Gupta, & Steckel, 1998), the *Guttman scale* (Gorden, 1977) and the *phrase completion scale* (Hodge & Gillespie, 2007) are examined as to their applicability to the evaluation method.

5 Presentation of the DST Evaluation Method

This chapter presents the evaluation method that is used to identify the technology concept with the highest potential for disruptiveness in the space sector. It consists out of a three step process that involves a combination of the Analytic Hierarchy Process, the Delphi method and Concept Scoring.

A prerequisite for the application of the DST evaluation method is the existence of a technology concept database, which can be used as a source for evaluation. The creation of such a database, however, is not part of this work. The methodology on the creation of a search strategy that can be used to create such a database is briefly elaborated on in Section 3.3.

5.1 DST Evaluation Method

The DST evaluation method is a process that consists out of a series of steps that each involve the evaluation and selection of a certain number of technology concepts. The ultimate goal of the method is to rate and eventually select the technology concept with the highest potential for disruptiveness out of the initial number of available concepts. In order to accomplish this, a combination of three different technology evaluation methods is applied. In each step of the process, a ranking is made and only the top n technology concepts are forwarded to the next step (with n being a number depending on the current step).

The level of work effort and evaluation preciseness increases progressively. With each step, the methods applied for the evaluation of the remaining technology concepts become more elaborate. This ensures that the highest possible evaluation accuracy and result quality are maintained while limiting work effort and time requirements. The three steps of this process and their respective methods are explained below.

The first step is called *pre-filtering*. In this step, the technology concepts is filtered in order to single out technology concepts that are too immature, do not have a sufficient disruptive potential or are outside of the search scope. Especially technology concepts where the available information is very limited or indistinct cannot be evaluated adequately by the following procedures and need to be filtered out. This step needs to be a part of the evaluation method and not part of the search strategy so that the technology scan can be performed without bias and according to the search rules defined by the strategy. The pre-filtering is done by the members of the DST project team. The goal of this step is to narrow down the database to not more than 200 technology concepts.

The second step is called *AHP pre-selection*. The top 200 (or less) technology concepts of the database, as established by the pre-filtering process, are evaluated by a group of experts. The Analytic Hierarchy Process is applied to break down the decision of the experts into four sub-decisions, those being the four categories of the STEP framework. Each expert is given the list with the technologies, accompanied by a short description of its main features and its maturity. The technologies are then rated on their performance on social, technical, economic and political factors. The ratings are inserted into a simplified concept scoring matrix and the total score of each technology calculated based on the mean score of the experts' answers. The experts are a group of 10 people that are not specialized in one field of work but rather have a broad understanding of all space technologies. They are familiar with space sector specifics as well as political, social and economic aspects. They also possess an above average amount of experience that enables them to roughly assess the potential value of a technology on the basis of the short description given to them. At the end of this process, the technologies are ranked and sorted into *technology domains* such as power, propulsion, materials etc. The goal of this step is to narrow down the database to 5 technology concepts per technology domain.

The third step is called *Delphi method*. The top 5 per technology domain technology concepts of the database are evaluated by a group of experts via a Delphi survey. The experts are rating the technologies on a number of criteria that correspond to the before mentioned categories of the STEP framework. These ratings are inserted into a detailed concept scoring matrix and the total score of each technology calculated based on the mean score of the experts' answers. The Delphi experts are a group of 10 people that are experts within their respective technology domain. They are able to fully assess technology concepts even with little knowledge about the characteristics of the technology. Additionally, they are familiar with the market dynamics corresponding to their specific field of application as well as political and social aspects. The goal of this step is to narrow down the database to not more than 1 or 2 technology concepts per technology domain.

The above described are guidelines as to how to perform the DST evaluation. Details of each step are not fully discussed here but left open to be determined during the application of the method and according to the given situation. An example of the application is given in Chapter 6.

5.2 Criteria Selection

For step two and step three of the DST evaluation method, different criteria are selected, on which the technologies are evaluated upon.

As already mentioned in the section above, the evaluation criteria for step two of the method, the AHP pre-selection, are the four domains of the step framework. Other than that, no further sub-criteria are selected in order to keep the work effort for the experts of this step inside a reasonable frame (up to 200 technologies must be read/understood and evaluated on 4 different aspects).

For step three, the Delphi method, the following criteria are selected and sorted into the STEP domains.

5.2.1 Social Criteria

Social Question 1 (SQ1): Compare the new technology (technology X) to the existing dominant technology (state of the art) in respect to environmental benefits.
Environmental aspects have become increasingly important in today society (Dunlap, 1991). Using a technology might lead to advantages or disadvantages to the Earth's environment. Society's opinion on the benefits of space technologies is partially governed by these benefits or drawbacks. A good example of how an environmental issue influenced a space program is the launch of Cassini-Huygens. The spacecraft had a radioisotope thermoelectric generator on board and a major civil movement against it fearing nuclear contamination in case of a launch failure was formed (Hoffman & Grossman).

Social Question 2 (SQ2): Are you aware of any ethical dilemmas or social problems associated with *technology X*?
Since the beginning of the space era in the 1950's ethical dilemmas have played a big role in the formation of space policy. Examples of ethical issues can be found in almost all manned spaceflight programs where the risk of a failure and the subsequent loss of life has to be weighed against the benefits of a manned mission. Other examples include the development of technologies that can be used for military purposes or the use of high resolution optical devices in satellites with regard to privacy protection. If the usage of the technology creates any ethical dilemmas, public perception might turn and decrease the potential for disruptiveness.

5.2.2 Technical Criteria

In the technical domain each technology is evaluated on its six most important performance attributes in comparison to the existing dominant (state of the art) technology. The attributes named A1 through A6 are different for each technology and are determined during the course of the Delphi method by the project team or by the experts. Examples for performance attributes are efficiency, reliability, lifetime or mass. If a technology fails to perform under the environmental constraints defined in Sub-section 2.3.2 it is not considered in this process and is filtered out during the pre-filtering phase. Therefore, attributes such as radiation resistance or vacuum resistance are not considered as valid attributes for the evaluation in the technical domain.

5.2.3 Economic Criteria

Economic question 1 (EQ1): Compare the new technology (technology X) to the existing dominant technology (state of the art) in respect to potential for spin-off.

The term *spin-off* (also sometimes referred to as *spin-out*) was formed in the context of space technologies in the 1950's and describes the usage of technologies or technology byproducts in commerce and outside of their main field of application (Beer, 2000). Technologies that have a potential for spin-off have potential for gains beyond their application as space technology and can therefore profit from favored development incentive.

Economic question 2 (EQ2): Compare the new technology (technology X) to the existing dominant technology (state of the art) in respect to production complexity and material cost.

The development of a technology is linked to its production complexity and material cost. If either of these two criteria is too high, the gain in performance might not justify the increase in cost and the technology might not get developed or be used.

Economic question 3 (EQ3): Compare the new technology (technology X) to the existing dominant technology (state of the art) in respect to operation complexity and maintenance cost.

High maintenance or operating cost might also have the same results as production complexity and material cost. A good example for a technology that was discontinued because of it operation complexity and the therewith associated cost is NASA's Space Shuttle Program (Cegłowski, 2005).

Economic question 4 (EQ4): Will the market (area of application) of area of application Y increase or decrease in the coming years?

A factor determining the success of a technology development is the potential market size or the number of potential applications of a technology. If this is high, then the technology development costs can be shared over a wide range of areas. If it is small then it could be that the technology might be too expensive to develop. Markets and areas of application can be affected by policy changes, mission types or technology advancements. For example, plans for colonization of the moon or mars will increase the market and area of application of life support systems and radiation shielding technologies.

5.2.4 Political Criteria

Political question 1 (PQ1): Do you know or can you think of any restrictions or regulations that can hinder the entry of technology X into the space sector?
Regulations/restrictions can be laws, directives, technical regulations, existing patterns or any other kind of restrictions that go against the development or usage of this technology.

Political question 2 (PQ2): In what timeframe do you anticipate this technology to be ready to be used in a space environment?
If the maturity level of a technology is too low and the expected timeframe for its development is too large, another technology might advance in the same domain and take its place before the technology is fully developed. This can decrease the disruptive potential of a technology. The importance of this question is determined by the scope of the respective research and the context it is used in.

Political question 3 (PQ3): Are you aware of any political incentive to promote or prevent the development of technology X (or their field of application)?
Decisions to promote or prevent a technology are often made with regard to political aspects and not only on the basis of the actual performance of a technology. Political decisions can be influenced for example by the need to secure employment, the existence of (trade) agreements, public pressure or be the result of lobby work. Govindarajan and Kopalle (2005) identified that commitments to existing technologies might limit the use of the potential disruptive technology. Within the space sector this factor is especially strong as technologies require an extensive investment in human capital and equipment. This initial investment and the common resistance to cannibalize existing technology development is an inhibiting factor against technology development (Kamien & Schwartz, 1982).

5.3 Weighing & Scoring

For the four domain of the STEP framework the pairwise comparison of the AHP process is performed as elaborated in Section 4.3. The weights for each domain that correspond to the comparison matrix in Table 7 are:

- Social: 4,5%
- Technical: 61,9%
- Economic: 22,4%
- Political: 11,2%

These weights are used in step two and step three of the DST evaluation method.

The weights for the sub-criteria in the Delphi method are assumed equal because no incontrovertible comparison can be done among them. Solely the PQ3 is weighted double the importance of the other two political questions because of the prior mentioned high importance of governmental influence on space technology development (compare Section 2.3). The weights are the following: SQ1 50%, SQ2 50%, EQ1 25%, EQ2 25%, EQ3 25%, EQ4 25%, PQ1 25%, PQ2 25% and PQ3 50%.

The weights of the performance attributes A1 through A6 are different for each technology and are determined during the course of the Delphi method by the experts.

For the scoring of the criteria in the AHP pre-selection and the performance attributes in the Delphi method a scale of -5 to +5 is used (modified zero to ten scale) where "–" indicates that the new technology is worse than the state of the art and "+" that the new technology is better. Zero means that both the new and the state of the art technologies perform equally.

For the SEP (social, economic and political) questions a modified quasi-Likert scale is used. As Jamieson (2004) and others argue, Likert scales fall within the ordinal level of measurement and using the mean is inappropriate for ordinal data. The SEP question might, therefore, have a Liker scale like look but the answers are in fact transformed to the interval scale. The answers differ from case to case and depend on the conditions set for the respective survey. They have to be devised individually for each application.

6 Case Study: Disruptive Technology Search for Space Applications

In Chapter 5 the DST evaluation method is described as a generic process applicable to any dataset of technologies and all domains of the space sector. This chapter presents the practical application of the method within the frame of a case study. According to Yin (1993) a case study can be of explanatory, exploratory or descriptive in its design. This case study can be characterized as both descriptive and exploratory. On the one hand, the goal is to show the feasibility of the DST evaluation method and familiarize the reader with the concept and the practical application of the method. On the other hand, this is the pilot application of the method before its potential application to other cases. The case study thereby also aims at identifying questions and drawing out implications for future applications and further research.

6.1 Research Objectives

The application of the DST evaluation method serves two main objectives as depicted in Figure 9.

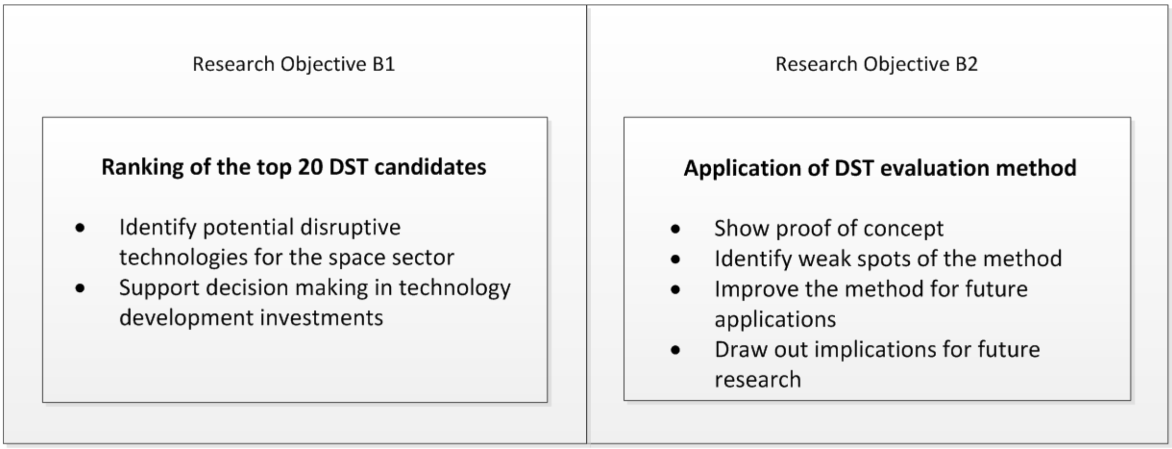

Figure 9. Research objectives of the case study.

The first objective is to make a ranking of the 20 currently available technologies that have the highest potential for disruptiveness inside four major technology domains: materials and processes, data handling, spacecraft electrical power and propulsion. These four domains are part of the European Space Agency's technology tree (European Space Agency, 2009). This is done on behalf of the European Space Agency who is looking to invest in the development of potentially disruptive technologies in order to overcome the merely moderate improvements that the expected evolution of current technologies can offer.

The second objective is to apply the theoretically developed evaluation method in practice and thereby show its feasibility and give the proof of concept. Further important aspects of this objective are the identification of weak spots, the improvement of the method in future applications as well as the drawing out of implications for future research.

6.2 Case Study Design

In this section the methodology of the application of the DST evaluation method is described.

6.2.1 Source of Data

The technology scan performed according to the developed search strategy was done in the context of the DLR study *Disruptive Technology Search for Space Application*. The three elements of the search strategy as implemented in the scan are depicted in the following.

Desk research included exploring news articles, science periodicals, technology journals, books and internet sources like web pages of companies and research institutes.

The technology database search included the following databases: the Ariadna database of the European Space Agency's advanced concept team, the ESA Invitation To Tender publishing system (EMITS), the ESA Innovation Triangle Initiative (ITI) database and the NASA External Government Technologies (ETG) data set.

For the expert survey, a database of experts was created by collecting the contact information of persons in managing and supervising positions in the world's leading technology corporations, universities, research institutes and space agencies. The questionnaire was send to the experts through an internet survey comprised of several questions focusing mainly on potential DTs in the field of work of the expert and his views on the future of the space sector. Out of 2,300 individuals contacted around the globe over 250 responded with 75% of the answers being of sufficient quality for the purposes of the study. Figure 10 shows the distribution of the respondents according to their field of expertise.

Through the broad technology scan, a total of over 1,000 technology concepts were ascertained. They constitute the DST candidate database and are used as a source for the DST evaluation method.

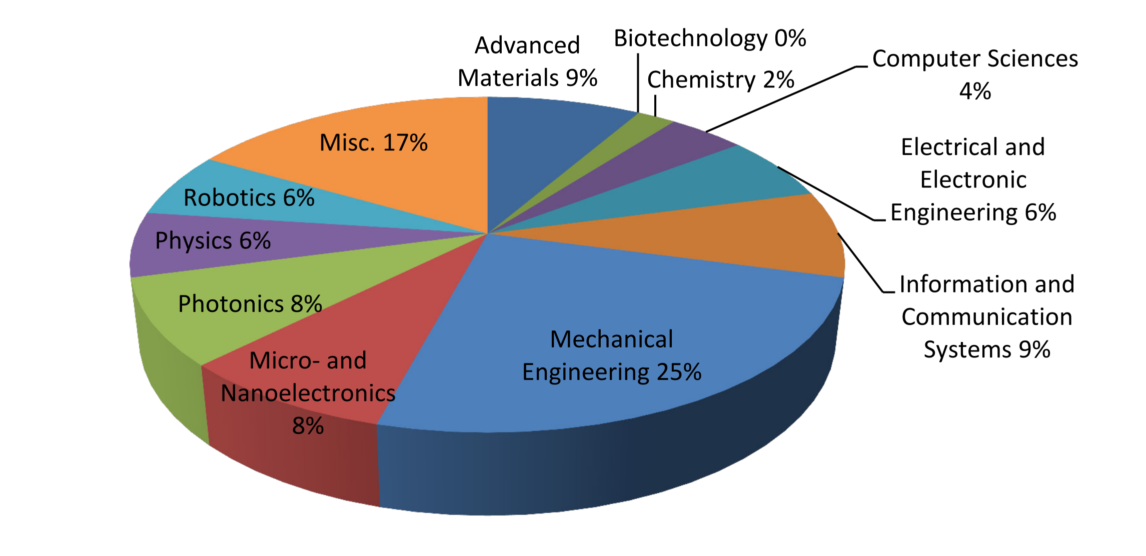

Figure 10. Distribution of expert survey respondents. Reprinted from *Technical Note 3: Broadcast Scan, Disruptive Technology Search for Space Application* (p. 28), by Deutsches Zentrum für Luft- und Raumfahrt, 2011, Unpublished. Reprinted with permission.

6.2.1 Method Design

The first step is the pre-filtering of the DST candidate database. This process is performed by the DST project team. Technology concepts that are too immature, do not have a sufficient disruptive potential or are outside of the search scope are deleted from the database. Maturity is decided on the basis of the Technology Readiness Level (TRL).

Table 8

The basic technology readiness levels

Technology Readiness Level	
Level	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical & experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in a space environment
8	Actual system completed and "Flight qualified" through test and demonstration
9	Actual system "Flight proven" through successful mission operations

Note. Adapted from *Technology Readiness Levels Handbook for Space Application* (p. 3), by European Space Agency, 2008, Noordwijk: ESA.

TRL is a scale used by ESA and NASA to describe the maturity of a technology. Table 8 shows the TRL with the corresponding description. Technology concepts with a TRL under 3 or with an expected development timeframe of over 30 years are deleted.

The second step is the AHP pre-selection. It is performed according to the DST evaluation method guidelines described in Section 5.1. The participating experts of the process are asked to rate the technologies on each of the four categories of the STEP framework in a scale of one to ten. A rating under 5 means that the new technology is worse than the state of the art, rating over 5 that the new technology is better. 5 means that both the new and the state of the art technologies perform equally. The ratings are inserted into a simplified concept scoring matrix and the total score of each technology calculated based on the mean score of the experts' answers.

The Delphi method is designed as an online questionnaire with three rounds. Häder and Häder (1998) argue that three round is sufficient for most Delphi surveys. After three rounds, no new arguments can be expected and the dropout rate increases as the motivation of the interviewees diminishes.

The SEP questions used in the survey are the same as presented in Section 5.2.

In order to compare the new technology to the dominant technology in the technical domain, a field of application is established for each technology. The field of application is defined as the field in which the new technology has the highest potential to overperform the state of the art techology. The definition of a field of application is done in order to create a common basis for a comparisson between the new and the old technology. Before the first round, a number of potentially important performance attributes are devised for each field of application. They are put together by the DST project team on the basis of literature research and personal knowledge. These attributes serve as the basis of the comparison between the state of the art and the DST candidate.

In the first round, the performance attributes are fed to the experts with the request to select the most important ones or name some of their own. A total of six attributes are selected or named. This is done for each field of application. The experts are also asked to answer the SEP questions. The answer options of the SEP questions and the corresponding values can be seen in Appendix 2 under *I. General Notes / Table legends.*

In the second round of the Delphi method, the experts are asked to rate the technologies on the six most important performance attributes that the DST project team selected on the basis of the answers the experts gave in the first round. The scale uses is the scale of -5 to +5 as proposed in Section 5.3. They are also asked to rate the importance of each attribute on a scale of 1 to 5. On this scale they have the liberty to rate each attribute individually. This method has the advantage that the experts do not have to pay attention to giving the attributes a total sum of weights of 100%, which would be an unnecessary challenge considering the number of six attributes. The ratings are transformed to percentages via the formula shown in Figure 11.

$$AP_1 = \frac{AR_1 100}{n} \div \sum_{i=1}^{n} \frac{AR_i}{n}$$

$$AP_1 = Attribute1\ Percentile$$

$$AR_1 = Attribute1\ Rating$$

$$n = number\ of\ attributes$$

Figure 11. Formula for the calculation of the performance attribute weights.

In the third round of the Delphi method, the experts are given a full record of the answers of the second round (attribute rating and attribute weight) including a mean score for each attribute. They are asked to reevaluate their answers and change it towards the mean if they agree with the assessment of the other experts. This round is performed via email and each expert is contacted personally.

In both the first and the second round the experts are given the opportunity to comment on their decisions. This serves the purpose of providing ESA with a better basis for their final decision making process. It also provides an indication of how substantiated the state of knowledge of each expert is and how big his motivation is.

6.2.1 Selection of Experts

For the AHP pre-selection process, ten distinguished experts are selected from within the department of System Analysis Space Segment of the DLR Institute of Space Systems. The reason for selecting these experts is that the people working in system analysis have a broad field of expertize as they are involved in work dealing with very diverse fields of space flight. Another reason for selecting these experts is that the expected compliance for this considerable amount of work is very high due to the personal relationships of the administrator of the process with the experts.

For the Delphi method the expert selection is carried out on a global scale. A database of experts in each of the four technology domains is created. As a start, all participants of the expert survey of the technology scan (see Sub-section 6.2.1) that expressed interest in the participation in further studies are contacted. Those who confirmed their participation for the Delphi method are inserted into the database. In order to expand this database, a second search for experts is conducted. Persons in managing and supervising positions in the world’s leading technology corporations, universities, research institutes and space agencies are contacted and asked for their participation. This second search is done with focus on those categories that still lack the wanted number of ten experts per category. Value is also placed on a balanced distribution of experts among different organizations and different countries in order to reduce bias. A total of 45 experts (at least ten in each category) are acquired for the Delphi method. A sample of the Delphi expert database is illustrated in Figure 12.

Space Secto	Field	Position	age	organization	country
Yes	propulsion		37	University	Austria
Yes	propulsion		42	Research Institute	Netherlands
Yes	propulsion		32	Company	Germany
Yes	propulsion		70	Governmental Agency	United States
Yes	propulsion		47	Governmental Agency	Japan
Yes	propulsion		32	University	Germany
Yes	propulsion		64	Company	United Kingdom
Yes	aerothermodynamics		49	University	United States
Yes	aerothermodynamics		47	University	South Korea
Yes	flight dynamics and GNSS		32	Research Institute	Spain
Yes	propulsion	Senior Technologist and the C		National Aeronautics and Space A	United States
Yes	propulsion	Senior Scientist/Technologist		National Aeronautics and Space A	United States
Yes	propulsion	Head of Propulsion and Aerot		European Space Agency	Netherlands
Yes	propulsion	Head of the Institute of Propu		German Aerospace Center	Germany
Yes	propulsion	Director of the Institute of Sp		German Aerospace Center	Germany
Yes	propulsion	Institute of Space Technology		Japan Aerospace Exploration Age	Japan
Yes	propulsion	Head Rocket Propulsion Depa		German Aerospace Center	Germany
Yes	propulsion			National Aeronautics and Space A	United States
Yes	on-board data systems		32	Governmental Agency	Netherlands
No	information and communication systems		78	University	United States
Yes	automation, telepresence and robotics		43	Research Institute	Germany
Yes	automation, telepresence and robotics		51	Governmental Agency	Canada
Yes	mission operation and ground data systems		32	Governmental Agency	France
Yes	space system control		43	University	Italy
Yes	on-board data systems	Institute of Communications a		German Aerospace Center	Germany
Yes	on-board data systems	Prof. at Institute of Space and		Japan Aerospace Exploration Age	Japan
No	on-board data systems	Aerospace Information Techn		University	Germany
Yes	on-board data systems	Head of Avionic Systems Dep		German Aerospace Center	Germany
Yes	system design and verification		41	Governmental Agency	France
No	renewable energy		45	Research Institute	Germany
Yes	electromagnetic technologies and techniques		48	Research Institute	Germany
Yes	electric, electronic and electromagnetic components		51	Company	Germany
Yes	thermal systems		52	Company	United Kingdom
Yes	thermal systems		55	Company	United States
Yes	spacecraft electrical power	Space Power Systems Group		Japan Aerospace Exploration Age	Japan
No	solar cells			Company	Germany
No	solar cells			Research Institute	Germany
Yes	materials and processes		43	University	United Kingdom

Figure 12. Sample of the Delphi expert database. Sample shows the diverse composion of the survey participants regarding age, organization and geographical position. Personal information is not shown.

6.2.2 Instrumentation and Data Collection

For data collection and evaluation the commercial spreadsheet application Microsoft Excel is used. The reason for selecting this application is that the initial database for the technology scan was done on this application and the need for a designated database tool is nonexistent.

For the Delphi method the online survey tool LimeSurvey is used. LimeSurvey is written in the general-purpose scripting language PHP. The survey results are exported into Excel spreadsheets.

The communication with the experts for the AHP pre-selection and the Delphi method is done via email by the author. The expert surveys are administered by the DST project team (AHP pre-selection) and the author (Delphi method).

6.3 Presentation, Analysis and Interpretation of Results

In this section, the results of the application of the DST evaluation method is presented, analyzed and interpreted. In Sub-section 6.3.1 the results of each step of the evaluation process are presented. The final ranking is analyzed qualitatively and interconnections between and among the results are established.

6.3.1 Presentation of Results

Through the broad technology scan, a total of over 1,000 technology concepts are ascertained. The pre-filtering process is applied to the initial database and after this screening, 220 technologies with a strong potential for disruptiveness remained.

The AHP pre-selection creates a ranking of the 220 technology concepts in the database. The top ten technologies of each category are shown in Appendix 1. The technologies selected to go into the Delphi method are not the top 5 technologies of each category like described in the DST evaluation method. The reason for this is that this being a project contracted by the ESA, they have the last saying in selecting the technologies for further evaluation. Their decision is based upon an internal selection process that takes into account ESA policy, long term intentions and current technology development. The technologies selected are: three out of the category data, six out of power, five out of propulsion and five out of materials.

Table 9

Delphi results ranked by category

Technology	Rank by domain	Total Score	
Metallic microlattice	1st	1,97	
Ceramic composite structures	2nd	1,43	
Graphite epoxy composites	3rd	1,31	Materials
Nanocrystaline diamond aerogel	4th	1,23	
Cathodic arc application of amorp. boron coatings	5th	1,21	
Chalcogenide-based reconfigurable memory	1st	1,13	
Holographic data storage	2nd	0,78	Data
Multicarrier signals	3rd	0,70	
Super/ultra capacitors	1st	2,16	
Silicon nanowire lithium ion-battery	2nd	1,65	
UltraFlex solar panels	3rd	1,48	Power
Aluminium-celmet for li-ion batteries	4th	1,21	
Quantum-dot solar cells	5th	0,52	
Bacterial nanowire	6th	0,31	
Alternative solid propellant CL-20	1st	0,89	
Micro-electric space propulsion MEP/NanoFET	2nd	0,88	
Transpiration cooling	3rd	0,74	Propulsion
Magnetoplasmadynamic thruster	4th	0,47	
Aerospike engine	5th	0,14	

These 19 technologies go into four different Delphi surveys, one for each category. The whole Delphi method results in the rankings shown in Table 9 and Table 10.

Table 9 shows the ranking per category and Table 10 shows the total ranking. The colors are used to better illustrate the positions of the categories in the total ranking. In Appendix 2, the documentation of the whole survey can be found. Of particular interest to the interpretation of the results are the comments given by the experts. They provide further information on the technologies, illuminate the thinking behind the experts voting and are also a strong indicator for the experts' motivation and state of knowledge.

Table 10

Delphi results ranked by total score

Technology	Total rank	Total Score	
Super/ultra capacitors	1st	2,16	
Metallic microlattice	2nd	1,97	
Silicon nanowire lithium ion-battery	3rd	1,65	Materials
UltraFlex solar panels	4th	1,48	
Ceramic composite structures	5th	1,43	
Graphite epoxy composites	6th	1,31	
Nanocrystaline diamond aerogel	7th	1,23	
Cathodic arc application of amorp. boron coatings	8th	1,21	Data
Aluminium-celmet for li-ion batteries	9th	1,21	
Chalcogenide-based reconfigurable memory	10th	1,13	
Alternative solid propellant CL-20	11th	0,89	
Micro-electric space propulsion MEP/NanoFET	12th	0,88	
Holographic data storage	13th	0,78	Power
Transpiration cooling	14th	0,74	
Multicarrier signals	15th	0,70	
Quantum-dot solar cells	16th	0,52	
Magnetoplasmadynamic thruster	17th	0,47	
Bacterial nanowire	18th	0,31	Propulsion
Aerospike engine	19th	0,14	

6.3.2 Analysis and Interpretation of Results

The total score indicates the performance of the technology in respect to the performance of the state of the art technology. The scale is a -5 to +5 scale where zero indicates an equal performance of both technologies.

The total scores show the comparison of the state of the art technology to the DST candidate. This implies that the technologies are comparable among each other even cross-domain insofar as the comparison is always done with respect to the state of the art. A higher score indicates a higher overperformance of DST candidate. As an example, Super/ultra capacitors offer a performance increase to current technology that is double the performance increase that alternative solid rocket propellant CL-20 can offer.

When using this data to support decision making in technology development investments one the following three approaches can be chosen.

When looking to invest in the technologies that have the highest potential for disruptiveness and offer the highest increase in performance compared to the state of the art, the total ranking of Table 10 must be considered. In this approach the technology categories and their interconnections are disregarded and only the raw numbers are crucial in the decision making process. This approach offers the benefit, that the selected technologies have the highest potential to be disruptive for their technology categories. The drawback of this approach is that the importance of the technology category for the whole space sector is not taken into account and that the disruption might not take place on a global scale (or not at all if the importance is very low).

The second approach is to invest in technologies that offer the highest overall benefit to the space sector. The increase in performance of a technology is put in context with the importance of its technology category. As an example, a propulsion technology with a 20% performance increase might offer a greater benefit to overall mission capabilities and cost reduction than a material technology with 60% performance increase. The reason for this disparity is that the technology categories are located on different system levels. Propulsion, for example, is considered a bottleneck technology and even small increases in performance can make a great difference in the overall performance of a space system.

The third approach is a combination of the latter two. From each category the technology with the highest score is chosen for development. This approach offers the benefit of an even development in all technology domains and ensures, that in each category, the technology with the highest potential for disruptiveness is chosen. Drawbacks for this approach are comparable to the ones of the first approach. The importance of the technology category is disregarded and a disruption may not occur.

7 Conclusions

7.1 Limitations of the Study

One of the biggest limitations of the study results out the theory of DST as formulated in Section 3.1. This theory focuses solely on product and process innovation and thus, disruptive space technologies and defined in a way that they exclude paradigm and position innovation. Especially position innovation, however, can be a major factor when investigating the disruptive potential of space technologies. The Committee on Forecasting Future Disruptive Technologies and the National Research Council (2009) have made categories to determine different kinds of DTs. These categories include:

- Enablers: A technology that makes one or more new technologies, processes or applications possible.
- Catalysts: A technology that alters the rate of change of a technical development or alters the rate of improvement of one or more technologies
- Morphers: A technology that when combined with another technology creates a new technology.
- Multiple technology disruption: A technology that replaces not only one, but multiple technologies. By its self the technology is not better than a single technology, but because of its combined function, the technology is better than the whole of the single technologies.

As can be seen, these categories do not comply with the definition of DSTs in this research and technologies that match these descriptions cannot be identified via the search and evaluation methods proposed here. They would, however, fit in the general concept if position and paradigm innovations, as defined by Francis and Bessant (2005), would be included in the theory. In order to include position and paradigm innovation and consider the above formed categories, a completely different approach has to be chosen. The theory of DST has to be adjusted to encompass the remaining two “P’s” and the search strategy, expert selection and criteria design has to be geared towards those two categories.

Further limitations of the study result out of the wide set scope for the identification of technology concepts. The heterogeneity of these technology concepts, even when sorted into broad technology domains like power or propulsion, is such, that the experts selected to evaluate them need to have different field of expertize. They cannot effectively be experts on all technologies alike. This was made evident by some of the comments of the experts, who stated during the Delphi survey that they knew only little about a specific technology because it was too specialized. This could be countered by reducing the range of the considered technology domains and focusing on only one. The formation of subcategories inside this one domain and the selection of dedicated experts for each subcategory will very probably increase the results accuracy and the quality of the evaluation method. It will also increase motivation of the experts to follow through the evaluation processes as all technologies will be of interest to them.

Another limitation of the study, made evident during the application of the DST evaluation method, was the time and manpower resources available for the AHP pre-selection step. Two hundred and twenty technology concepts with four evaluation categories per concept result in a total of 880 choices the experts had to make. Given the time requirements and the amount of experts selected for this task, the results can be described as only a rough assessment of the technology concepts. An allocation of more experts, a larger timeframe and some additional incentive (e.g. financial compensation) could increase the accuracy and quality of the results.

7.2 Implications for Future Research

As mentioned above, one goal for future researchers could be to include paradigm and position innovation in the scope of the DST theory. However, product and position innovation cannot be evaluated in the same manner. A different approach than the one utilized for product innovation evaluation needs to be developed for position and yet another for paradigm innovations. For position innovations, the criteria of the search strategy need to be adjusted to include technologies that are not new and do not provide an obvious increase in performance but have the potential to fulfill one or more of the categories established by the Committee on Forecasting Future Disruptive Technologies. Also, the mindset of the experts and possibly the selection of them need to be changed. When looking for position innovation it is important to have people with experience in a broader sense and an open mind as experts, which will enable them to recognize a technology with the potential for disruptiveness in this category. Furthermore, the criteria need to be altered. The focus, especially in the technical domain, has to be more on the future importance of the criteria and not on their current importance. Finally, the terminology, particularly the word technology, will have to be revised in order to avoid confusion with the special case of technology evaluation. Paradigm innovation does not necessarily involve the introduction of a (new) technology. This needs to be taken into account when devising an evaluation method for concepts with disruptive potential in the paradigm category.

The dynamics of the space sector provide further implications for future research. The space sector analysis performed in this study describes the space sector as a quasi-monopsony market with governmental institutions being the main investors in space technologies (compare Sub-section 2.3.1). This, however, is changing. Commercial space exploitation is gaining importance for the space sector in light of ongoing budget cuts and the privatization of the space sector (Tkatchova, 2011). This change in actors can lead to a change in innovation dynamics, pathways of technology development and disruption mechanisms currently in effect.

Important lessons learned from the Delphi method are summarized below:

- The expert selection is the most important element of the Delphi method. Large discrepancies regarding motivation and knowledge were observed among the experts. The selection of the right experts guarantees not only a lower dropout rate but also a much higher quality of answers. A noticeable difference was observed between experts that were randomly acquired and those that participated in the study based on recommendations, even if the one recommending them did not have any liaison to the project team.
- A second selection process of experts based on their performance in the first round of the Delphi is advisable. During the course of the survey some experts excelled while others delivered only mediocre results. A reevaluation of the experts could be done according to the quality of their answers regarding the comments or/and the time they spend for the completion of the survey.
- An inquiry on the experts' knowledge on a specific technology is essential. Some experts may or may not know a great deal about a specific technology. This assessment has to be made in order to increase or decrease the weight of the expert's opinion if necessary.

7.3 Recommendations

As a next step in the evaluation process of the technologies, the roadmapping of the technologies with the highest potential for disruptiveness is recommended. Technology roadmapping is a needs-driven technology planning process that helps identify, select, and develop technology alternatives to satisfy a set of needs (Garcia & Bray, 1997). In this case, these needs can be defined as the specific conditions needed in order for the technology development to take place. The roadmap shall most notably contain information on the necessary development steps a potentially disruptive space technology has to accomplish before it matures. In this, the roadmap will provide a framework to help plan and coordinate the technology development.

It is also recommended that the results of this study are reevaluated and verified in the future. To corroborate the disruptive potential of the highest ranked technologies, a repetition of the evaluation process at least every five years is recommendable in order to keep up with current developments on a technological and socio-political level. A repetition of the process will also be an important step in the validation of the DST theory and will contribute to the refinement of the process.

The implementation of scanning, monitoring and tracking techniques as a parallel task to the technology evaluation process is also recommended. SMTs were deemed impractical for the current research, as they require an extensive time investment over a longer period of time. It would, nonetheless, be advisable for any organization that is looking to establish an early warning system for disruptive space technologies to implement scanning monitoring and tracking techniques as they will mitigate the chance of unexpected DSTs arising. One way this can be done is by building upon the created technology database and integrating a technology tracking system.

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Appendix 1

AHP Pre-Selection Results

Materials

Technology Name	AHP Factors: Social	Technical	Economical	Political	Total
Ceramic Composite Structures	6,00	7,83	6,50	6,83	**7,35**
Graphene	5,86	7,86	5,86	6,29	**7,15**
Metalic Microlattice	5,40	7,80	6,00	6,20	**7,11**
Graphite Epoxy Composite	5,40	7,80	5,60	5,80	**6,98**
Boron Nitride Nanotubes	4,20	7,40	6,40	5,60	**6,84**
Elastic Memory Composite Material	6,00	7,50	4,83	6,00	**6,67**
Carbon Reinforced Plastics (CFRP)	5,50	7,17	5,17	5,33	**6,44**
Biomimetic Adhesive Polymers Based on Mussel Adhesive Proteins	5,83	7,00	4,50	6,33	**6,32**
Electroactive Polymers	5,33	7,00	5,00	5,50	**6,31**
Basalt Fibers	4,83	6,50	6,50	5,17	**6,28**

Data

Technology Name	AHP Factors: Social	Technical	Economical	Political	Total
Quantum computing	7,00	9,00	6,50	7,17	**8,15**
DNA Computer	5,17	8,17	5,50	5,83	**7,18**
Holographic Data Storage	5,80	8,00	5,40	6,40	**7,14**
Quantum Sensor	6,17	7,83	6,00	5,67	**7,11**
Chalcogenide-Based Reconfigurable Memory Electronics	6,17	7,33	6,50	6,17	**6,97**
Quantum communication	7,00	7,50	6,00	5,50	**6,92**
Wireless data handling	5,20	7,20	6,00	6,00	**6,71**
Noise-Robust Speech Recognition for Speech Computer Control	6,60	7,00	5,40	7,00	**6,63**
Three-dimensional integrated circuit	5,67	6,83	5,67	5,83	**6,41**
Gallium Nitride semiconductor technology	5,60	7,60	3,20	5,60	**6,30**

Power

	AHP Factors				
Technology Name	**Social**	**Technical**	**Economical**	**Political**	**Total**
High temperature superconductors	6,29	8,00	5,57	6,43	**7,21**
UltraFlex solar panels	8,00	6,00	9,00	9,00	**7,10**
Advanced Stirling Radioisotope Generator (ASRG)	4,29	8,00	5,71	5,57	**7,05**
Quantum-Dot Solar cell	6,67	6,83	7,17	6,67	**6,89**
Unitized regenerative fuel cell (URFC)	6,00	7,40	5,60	6,40	**6,83**
Holographic Planar Concentrator Photovoltaic (PV) Module	6,80	7,60	4,40	7,00	**6,78**
Aluminum-Celmet for Li-Ion Batteries	5,67	7,33	5,83	5,67	**6,74**
Silicon Nanowire Lithium-Ion Battery	5,20	7,40	5,40	5,60	**6,66**
Nano Composite Solar Cell	6,20	6,80	6,40	6,20	**6,62**
Super/Ultra capacitors	5,33	7,00	6,33	5,17	**6,58**

Propulsion

	AHP Factors				
Technology Name	**Social**	**Technical**	**Economical**	**Political**	**Total**
Laser propelled light craft	5,50	8,00	6,17	5,50	**7,20**
Altitude compensating nozzles	5,20	7,80	5,40	5,80	**6,93**
Fission Fragment Rocket Engine (FFRE)	4,50	7,83	5,67	5,00	**6,89**
Alternative Solid Propellants: CL-20	5,20	7,80	4,80	5,80	**6,79**
Micro Electric Space Propulsion (MEP)/ NanoFET	5,33	7,17	6,17	5,83	**6,72**
Ambient Plasma Wave Propulsion	5,40	7,00	6,20	5,40	**6,57**
Magneto-plasmadynamic thruster (MPDT)	5,40	7,40	4,60	5,80	**6,51**
Magnetic Sails	5,00	7,17	5,50	5,33	**6,49**
Variable specific impulse magnetoplasmarocket (VASIMR)	5,20	7,20	5,20	5,40	**6,46**
Electrodynamic Tether	5,17	6,50	6,67	6,17	**6,44**

Appendix 2

Declaration of Academic Honesty

I hereby declare to have written this diploma thesis on my own. All parts of this paper that are cited literally or in a rough summary from publications or other secondary material are recognizable and I have clearly defined them with their respective references.

Berlin, Mail 23, 2012