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Space System Analysis

Disruptive Technology Search for Space Applications
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DISRUPTIVE
SPACE TECHNOLOGIES

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List of Abbreviations

ACRONYM	EXPLANATION
AOCS	Attitude and Orbital Control System
ARTES	Advanced Research in Telecommunications Systems
CTP	Science Core Technology Programme
DHS	Data Handling System
DLR	German Aerospace Center (German: Deutsches Zentrum für Luft- und Raumfahrt e.V.)
DST	Disruptive Space Technology
DSTs	Disruptive Space Technologies
DT	Disruptive Technology
EC	European Commision
ECI	European Components Initiative
EEE	Electric, Electromechanical & Electronic
EOEP	Earth Observation Envelope Programme
EPS	Electric Power Supply
ESA	European Space Agency
FLPP	Future Launchers Preparatory Programme
GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
GSTP	General Support Technology Programme
MREP	Mars Robotic Preparation Programme
PEST analysis	Political, Economic, Social and Technological analysis
PESTEL analysis	Political, Economic, Social, Technological, Environmental and Legal analysis
Proba	Project for On-Board Autonomy
SLEPT analysis	Social, Legal, Economic, Political and Technological analysis
STEEPLE analysis	Social, Technological, Economic, Environmental, Political, Legal and Ethics analysis
TCS	Thermal Control System

TRL	Technology Readiness Level
TRP	Basic Technology Research Programme
TTP	Technology Transfer Programme
WP	Work Package

Executive summary

This TN reports on Work Package (WP) 2000 of the proposal, which is the *Space System Analysis*. The main purpose of this work package is a literature research and the description of the space segment. It fits within the overall research as the space system analysis part, highlighted in the overall structure of the research, depicted in Figure 1. In this figure, the second chapter documents upon the creation of the Theory of DSTs by exploration of the Innovation Theory and a Space Sector analysis. This theory will be used throughout the project but especially within the guidelines development part in TN02. The third chapter facilitates this research by providing a Spacecraft System Categorization which sets the technology search scope for the broadcast scan in TN02. These chapters are elaborated in more detail below.

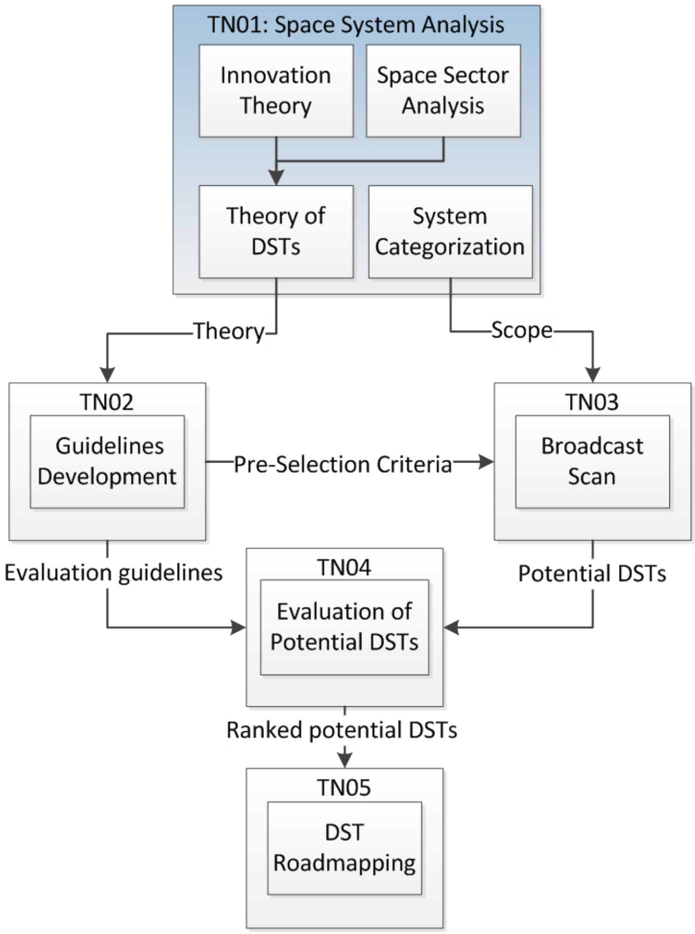

Figure 1: Overall structure of research

Chapter 2: Space Sector Analysis

This chapter shows a literature study on innovation in general, followed by a literature review of DTs. A DT is an exemption to the incremental/radical innovations paradigm, which Christensen (1997) classifies as sustaining innovations, because companies marketing these incremental/radical innovations continue to serve the same customers with the intention of sustaining their position in the market. The opposite of these sustaining innovations are DTs, which are technologies that disrupt the market of existing technologies exploited by incumbent companies. In practical terms this means that incumbent companies exploiting a dominant technology are being disrupted by new entrants exploiting a new technology. Examples of incumbents disrupted by new entrants are illustrated in. The table shows the dominant technology, the Disruptive Technology introduced by a new entrant, the disruptive attribute that constitutes the biggest source of change in the perceived customer value and therefore sparked the disruption and the period of disruption.

Table 1: Examples of DTs

Dominant technology (Incumbent)	Disruptive Technology (New entrant)	Disruptive attribute	Period of disruption
Workstation	Personal computer	Affordability	1980's
5.25 inch disk drive	3.5 inch disk drive	Size, weight (laptops)	1980's
Compact Cassette	Compact Disc	Sound quality, capacity	1990's
Chemical photography	Digital photography	Capacity, development cost	2000's
Discman	Mp3 player	Portability, capacity	2000's

For this research the following definition of DTs was adopted:

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 performance mix, which is valued more by the customer than the one of the dominant technology.

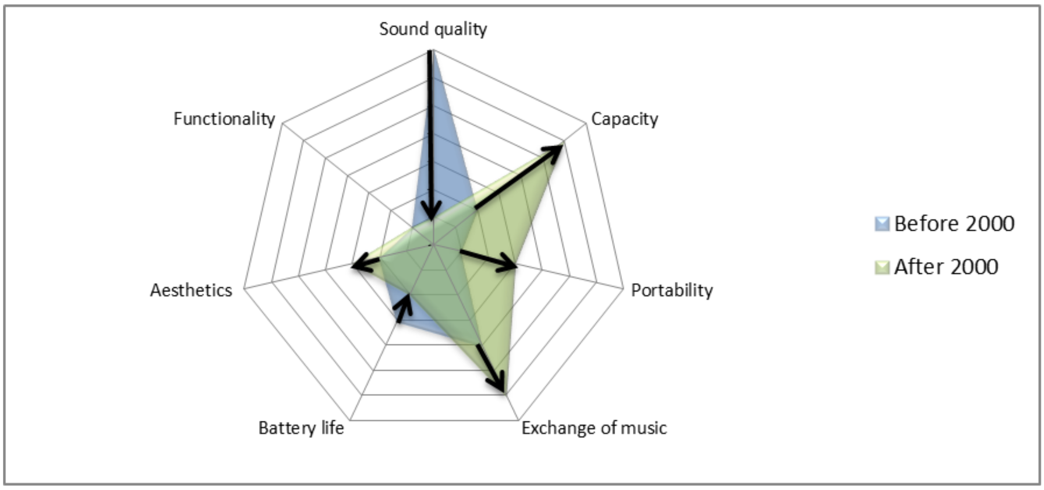

Figure 2: Change in perceived performance mix of portable music players. A higher score means a better performance on this attribute. For illustration purposes only

As illustrated by the definition, the core of the theory of DTs is the change of a performance mix. This mix is an illustration of the performance on several attributes of a technology. The key point is that the markets' perception of which performance attributes are important changes and that is why a technology is able to become disruptive. An example of how this changed in the portable music market is illustrated in Figure 2.

After analyzing several past disruptions within the space sector, the conclusion was made that space technologies have a similar process of disruption. The former technologies all had a different mix of performance attributes compared to a dominant technology and could therefore get a foothold within the market. Examples of several dominant space technologies that have been disrupted are illustrated by Figure 3.

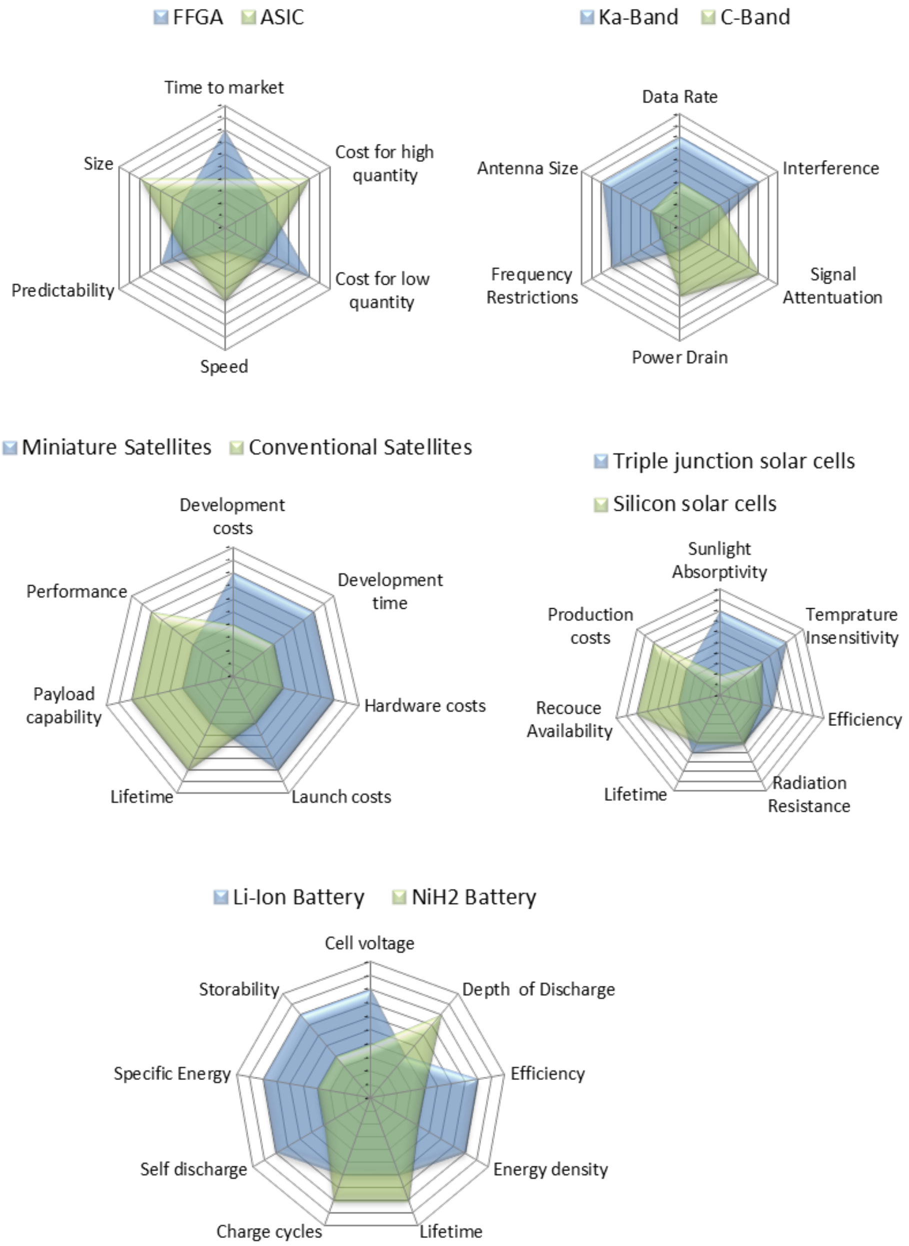

Figure 3: Performance mixes of Past DST (blue) vs. Former Dominant Technology (green)

The space sector infrastructures with respect to technology development and the innovation dynamics of the space sector are analyzed in order to map technology developments within the space sector. This includes an analysis of the key players in technology development both in and outside the space sector. An analysis of the space sector infrastructure with respect to technology development has led to the following conclusions:

- Development paths are usually long and time consuming and not always continuous as technology development in later stages mostly depends on mission application, which is not guaranteed.
- Technology development can be divided into two kinds: push and pull, where the former means it is developed due to the expectation of an up-coming need and the latter means the development is driven by technological requirements of an actual mission.
- There are several technology programs, divided over different levels throughout the space sector, supporting push development through basic technology research.
- Technology pull constitutes the largest part of technology development in the space sector. This kind of technology development does however not lead to major improvements of the space sector in general because of a relative small degree of freedom in taking risks.
- After analyzing several past disruptions, is was concluded that disruption in space does not include the disruption of markets and companies
- Disruption in space does include the over performance along different performance dimensions.

From the space sector analysis and the past disruptive technology analysis, a new theory of disruption by case of the space sector is developed namely: Disruptive Space Technologies (DST). A DST is defined as the following:

A Disruptive Space Technology is an emerging technology, which disrupts the status quo of the space sector by radically improving on the performance along a discontinued perceived performance mix of a part of the market.

Chapter 3: Spacecraft System Categorization

Chapter 3 is focused on the system categorization of a spacecraft. It analyzes the functions and interdependencies of the various subsystems. The goal is to determine the possible impact of future technology developments on a spacecraft or subsystem more efficiently and accurately. The conclusion is a preliminary definition of the search scope to narrow the search space down to critical technology fields. These technology fields are:

- Photonics (usage of light/ optical technology for various applications like communication and measuring)
- Advanced Materials (lightweight materials, fibers)
- Micro- and Nanoelectronics
- Biotechnology
- Information and Communication Technologies
- Robotics

1 Introduction

This Technical Note (TN) reports on Work Package 3000, which is the *Space System Analysis* part of Project 4000101818/10/NL/GLC. The main purpose of this work package is a literature research and the description of the space segment. The work package forms the basis for the following work packages. It is divided into two main parts, i.e. two major sub-work packages. It fits within the overall research as the space system analysis part, highlighted in the overall structure of the research, depicted in Figure 1-1.

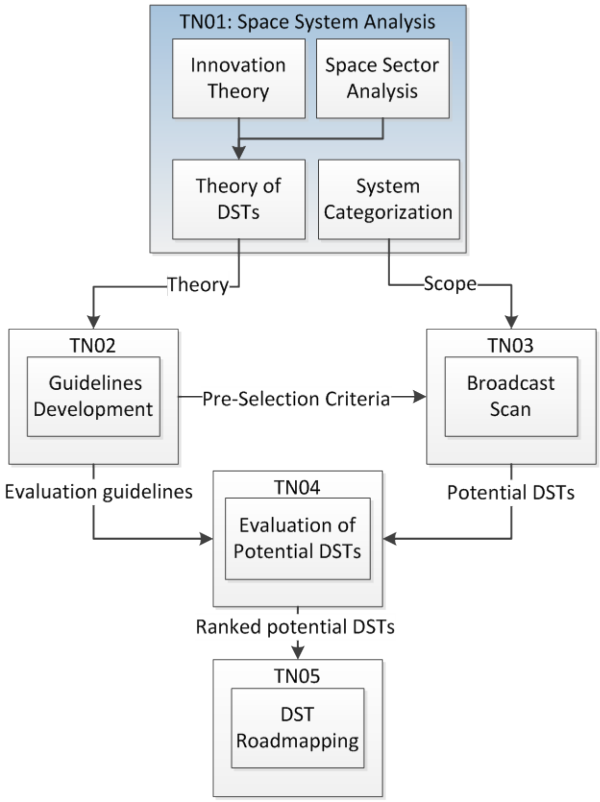

Figure 1-1: Overall structure of research

The first is the Space Sector Analysis in Chapter 2, covering WP 2100 displayed in the Management Proposal. It provides an overview over the administrative environment of the space business, focusing on a technology development perspective. In answering the first and second subtasks of the Statement of Work's Task 1 (Analysis), this chapter deals with the terminology of technology, innovation and also describes some different views on the theory of Disruptive Technologies, explaining the criteria that make a technology disruptive. Furthermore the necessity of adapting this theory for space in a new DSTs theory is elaborated (Section 2.1). In the following Section, 2.2, the space sector's Research and Development environment is described and an overview is given of space sector's infrastructure with respect to R&D. After this (Section 2.3), a collection of key-players in advanced technology developments, like research institutes, departments, networks & clusters are presented. Section 2.4 contains a more in depth analysis of the technology development within the European space sector. This is divided among the push-pull technology development axis. Section 2.5 presents a new theory of what Disruptive Technologies are for the space sector (DSTs).

The second and final subtask is worked off in chapter 3. It contains the results of WP 2200, *Spacecraft System Categorization*, and is focused on the actual spacecraft. It analyzes the functions and interdependencies of the various subsystems. Generally, the goal is to determine the possible impact of future technology developments on a spacecraft or subsystem more efficiently and accurately. The conclusion of WP 2200 is a preliminary definition of the search scope to narrow the search space down to critical technology fields. Although review of standard technology is also part of WP 2000 (in sub-work package 2300), this will be done in a later phase of the project, since it requires input from WP 4000, the Broadcast Scan.

2 Space Sector Analysis

The task of this sub-work package is the definition of the term *Technology*, its meaning and how it is developed in the space sector landscape. A similar approach is chosen for the term *Innovation* and in the end a definition of what *Disruptive Space Technology (DST)* actually means, is given. Furthermore important fields of research will be pointed out, with respect to general situations and processes in which a technology is developed and matured to a usable condition.

2.1 Literature Research

This section elaborates on Disruptive Technologies (DTs) and what their relations to several common types of innovations are. The theory of DTs, first described by Bower & Christensen [RD 1] has become somewhat of a buzzword in business, innovation and technology management literature. It describes the disruption of dominant technologies by new technologies which are *"simpler, more convenient and lower cost"* [RD 2]. The work package uses a zoom-in approach by firstly explaining and providing definitions of the terms technology and innovation. Secondly, it will provide an overview of what DTs are, according to literature in light of the previous definitions.

2.1.1 Technology

Nowadays the word technology is often associated with complex machinery, consumer electronics or software. However the word in ancient Greek '*technología*' (Wikipedia, 2010) has a broader meaning. The word's translation is basically twofold: *Téchne* which is a craft or art and *Logía* 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:

- 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 definition applies:

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

While technology is any practical application of knowledge, innovation is doing something new. This is elaborated within the next section.

2.1.2 Innovation

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 means according to several experts like Tidd et al. [RD 3] & Ayres [RD 4]: "*to make something new*". Therefore this research will adopt the following definition:

> *"Innovation is the introduction or application of a new idea or invention which 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 [RD 5]:

> *"Innovation = invention + exploitation"*

Innovations can be classified according to their type, their novelty and their evolution over time. These three distinctions will be elaborated in the next sections and will serve as classifications for the new DST definition as this is also a subset of the innovation management theory.

2.1.2.1 Innovation Types

According to Francis [RD 6] innovations can be classified into four broad types called the 4p's of innovation. These 4p's and their examples when applied to space are:

- Product innovation – Improvements in the products or services an organization offers. Example: A new propulsion system which allows for more cost-efficient space missions.
- Process innovation – Improvements in the way products or services are created and/or delivered. Examples:
    - Concurrent Engineering instead of sequential engineering
    - Simulations of missions to improve efficiency
    - Model Based Development and Verification
    - Virtual Prototyping instead of using hardware prototypes.
- Position innovation – Improvements in the context in which the product or services are introduced. Example: A space company changes its focus from doing science missions to communication missions.
- Paradigm innovation – Improvements in the underlying mental models which state what the organization or company does. Example: A paradigm change from expanding human frontiers (exploration of celestial bodies like the Moon) to improving human life (satellites monitoring the environment or the global positioning system)

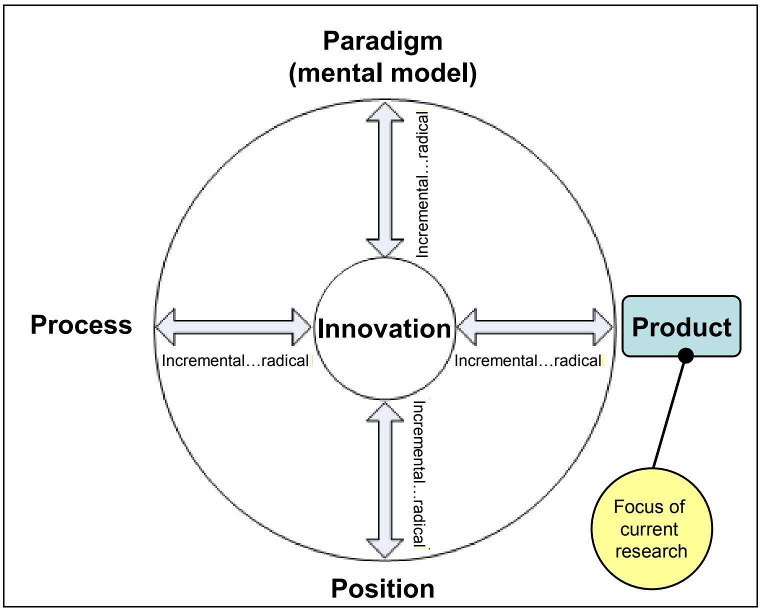

Figure 2-1: Tidd's (2005) wheel on the 4P's of Francis [RD 6] with the addition of the focus of this research

Tidd et al. [RD 3] put these innovation categories in an innovation wheel illustrated in Figure 2-1. DSTs are product innovations, because technologies are always products of research and development programs. DSTs are also possible in the process innovation field because a process is a technique which can also be a technology. However, the study team regards only products, something tangible a technology applicable to DSTs. The results of this project will therefore only be applicable to innovations in the product innovation category. Innovations can sometimes be classified in more than one category, e.g. the commercialization of the space sector which is clearly a paradigm innovation. The product of commercial space companies can however be designated as product innovations.

2.1.2.2 Degree of Novelty in Innovation

The next group of innovation classes focuses on the impact of an innovation within the market. After an exploratory research in the theory of innovation, the conclusion has been drawn that multiple taxonomies for innovation categories are used: "*As the vocabulary used to describe innovation has grown and evolved, scholars naturally generate multiple taxonomies which are at times overlapping, redundant, or divergent*" [RD 7]. Supporting this is a literature review from Garcia & Calantone [RD 8] which found that in the just 21 empirical studies researched, 15 different constructs for describing various aspects of innovation were used. Even the most basic fundamental definitions resulted in various terms. For example; Radical Innovations are also classified as: Breakthrough-, Discontinuous-, Transformative- or Creative Destruction innovations. To eliminate any further confusion, a framework is illustrated in Figure 2-2 using only the terms that from now on are used in this research. This framework is derived from the original framework of Henderson & Clark [RD 9] and is also elaborated in Tidd et al [RD 3].

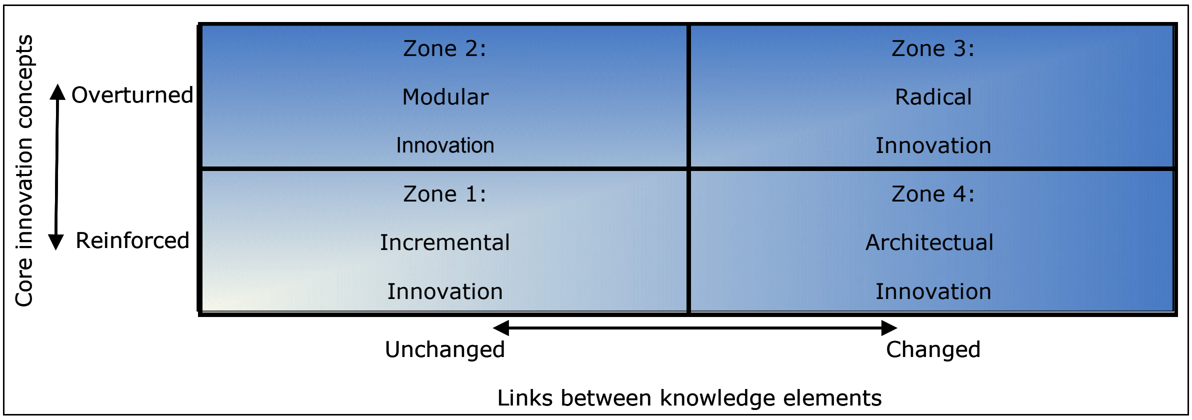

Figure 2-2: Novelty framework adopted from Tidd et al. [RD 3]

According to Henderson & Clark [RD 9], the novelty framework divides the innovation types across two axes: the core innovation concepts and the links between knowledge elements. The core innovation concepts deal with the degree of novelty in sub parts of a technology or process. These can either be reinforced or overturned which respectively means: improved or kept the same and radically changed or innovated. The links between knowledge elements mean innovations in the overall system area such as the structure but not the sub parts itself. These can be unchanged or changed (innovated). As stated earlier, the zones indicate the different possible impacts of innovations. The zones and some examples with respect to an example (microprocessors) are elaborated next.

Zone 1:

Contains incremental innovation, these innovations are the most common innovations as they improve upon already existing products in existing markets. These innovations generally generate the largest income for a company [RD 10]. Incremental innovations are usually used to stay with or get ahead of the competitors. Leifer et al. [RD 11] describe an incremental innovation as the exploitation of a technology. An example of the successful application of this is in the field of microprocessors. Incremental innovations pushed the processor speed of the Intel Pentium I from 60 MHZ to 300 MHZ [RD 12]. This increase in performance was caused by small changes and improvements in the product.

Zone 2:

Contains modular innovation, where only a part of a product or service is completely innovated. For the example of microprocessors, this could be the usage of a new socket, but also a new processor itself could be a modular innovation as viewed from the entire computer. The classification of a modular innovation therefore depends on the level of aggregation used to view the innovation.

Zone 3:

The third zone contains the highest amount of terms which all have similar meanings. In this research the term Radical Innovation shall be used. Leifer et al. [RD 11] describe a Radical Innovation as the exploitation of a new technology. Radical Innovation is a form of innovation which is the hardest to reach. It means the creation of a product according to a new architecture and of some or all the modules. Even though the development of a Radical Innovation might take substantial amounts of time and money, it usually offers the biggest reward. An example w.r.t. processors could be the creation of an electronic quantum processor which is a completely new technology based on a new architecture and modules.

Zone 4:

Zone 4 contains the architectural innovation. This type of innovation focuses on situations where an existing product or service is transformed into different product or service with the same subparts but organized in a different way. This is usually done to focus on a new group of customers. An example of this for processors would be the dual or quad core processors where the number of cores and thus the architecture changes. Like with modular innovations, the classification depends on the aggregation level. Because of this, an architectural innovation can also be seen as a Radical Innovation in the architecture.

The framework of 4Ps can be used in classifying DSTs. Usually a DST represents a significant improvement in either or both of the axes. Therefore we can state that a DST can be a modular, architectural or Radical Innovation but not incremental as this cannot be disruptive. The distinction between modular, architectural or Radical Innovation is not that important because of the before mentioned aggregation level, therefore the term of Radical Innovations applies to DSTs.

2.1.2.3 Innovation Evolution over Time

Eventually every successful innovation, once it has been introduced to the market, will evolve from a Radical Innovation to an innovation that needs incremental innovations to continually increase its performance. This evolution of innovation within one technology can be classified into three phases, identified in the Model from Abernathy & Utterback [RD 13]:

- Fluid phase
- Transitional phase
- Specific phase

One way to illustrate these phases in technology evolution is by using an S-Curve. It is sometimes also referred to as a way to illustrate the Life Cycle of a technology. The S-Curve was first explained by Beer [RD 14] who stated that: *"Technological change can be categorized as a series of overlapping S-Shaped curves"*. The idea was then worked out further by Foster [RD 15]. The three phases of the Abernathy & Utterback model [RD 13], with respect to an S-curve are illustrated in Figure 2-3.

The *fluid phase* is the concept phase where the technology is a Radical Innovation or DT that begins to emerge. The technology's major competitor is the established dominant technology, and the dominant design (architecture or technology platform) for the innovation is not yet set. The new technology makes slow progress in performance, because the technology is not well known and may not attract the attention of other researchers. Also certain obstacles must be resolved so that a new technology can be translated into practical and meaningful improvements in a product.

The *transitional phase* is the phase where the new technology crosses a threshold after which it makes rapid progress (resulting from combined, accumulated research effort). This stimulates the research on the new technology, which in turn leads to rapid improvements in its performance. Its main opportunities for innovation are modular and architectural innovations, and these innovations are also its biggest threats.

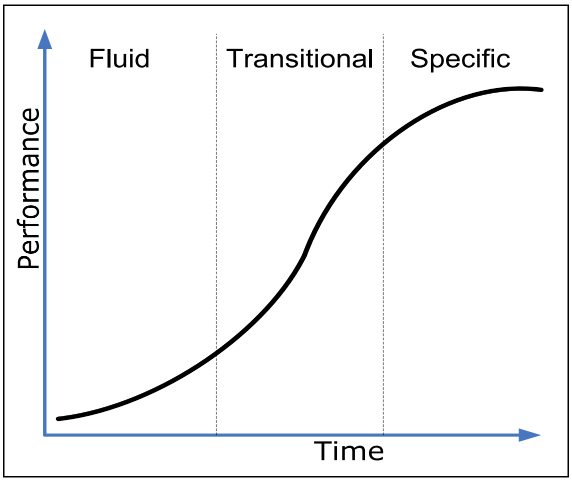

Figure 2-3: S-Curve with its phases

The *specific phase* comes after a period of rapid improvement in performance. The new technology reaches a period of maturation after which improvements in performance occur slowly until it reaches a certain level. Sahal [RD 16] proposes that the rate of improvement in performance of a given technology declines because of limits of scale (e.g. things become either impossibly large or small) or system complexity (e.g. things become too complex to work perfectly). When these limits are reached, the only way to maintain the pace of performance increase is through radical/disruptive system redefinition. In this phase a technology has the highest chance of becoming replaced by a Radical Innovation or a DT.

It is important to note that S-Curves have one major drawback: they can measure only one performance dimension [RD 17]. This is usually the primary performance value on which a technology is measured (like efficiency with solar panels). However, the consequence is often a blind sightedness to other important attributes (like life time and mass in the case of solar panels). Therefore we propose to use the theories of S-Curves in further applications only as an illustration method in light of their perceived performance mix, which will be explained next.

2.1.2.3.1 Perceived Performance Mix

Companies marketing technologies attempt to satisfy customer demand. The demand or requirements for technology performance differ with every customer. In marketing literature this heterogeneity in customer demand is called customer-perceived value [RD 18]. In this research we are trying to determine the broad performance of a technology as stated by a mix of performance attributes like e.g. cost, speed, mass, efficiency. Therefore we implement a new concept of *perceived performance mix* which is the performance mix as perceived valuable by a part of the market, or a market niche.

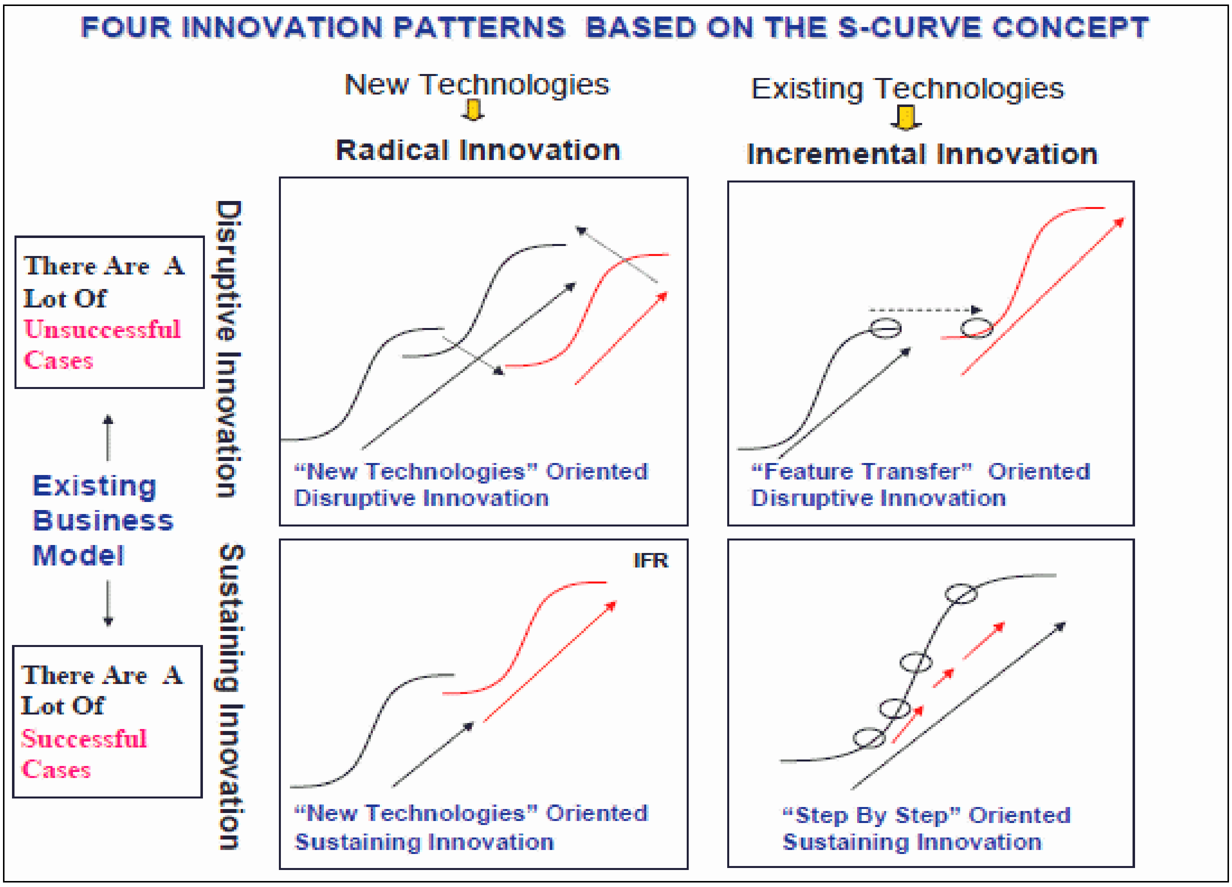

Figure 2-4: The different S-curves in innovation by Sawaguchi [RD 19]. The black line represents the 'business as usual' while the red line represents the type of innovation.

Figure 2-4 illustrates the different types of innovations in relation to their S-Curves:

- Top left: Radical replaced by Disruptive innovation
- Bottom left: Dominant replaced by Radical innovation
- Top Right: Incremental innovation replaced by Disruptive innovation
- Bottom Right: Incremental innovation improving an innovation over time

The Disruptive Innovation/Technologies will be more extensively elaborated in the next section. The different innovations in this figure are illustrated in red, while dominant technologies are illustrated in black S-Curves. In the case of disruptive innovations in the upper cases, it can be seen that the perceived performance mix alters (black line changing to a red line) and therefore enables market opportunities for the development of a new technology. With normal sustaining innovations in the lower two cases the performance demanded by customers stays in line with the normal technology development.

A method of illustrating the perceived performance is by using a radar chart, as this can show which performance attributes are perceived as valuable by the customer. A change of perceived performance mix over time is illustrated in Figure 2-5. In this example the change of the perceived performance mix sparked the disruption in the portable player market.

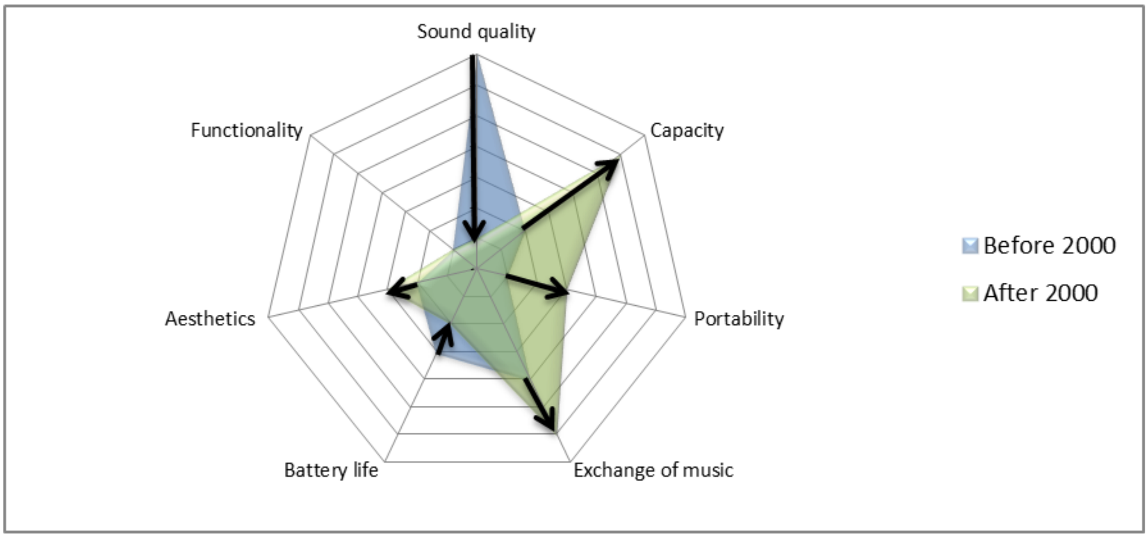

Figure 2-5: The perceived performance in portable music player in the Discman era.

In this research a DST is defined as a technology which performs better on the perceived performance mix than a dominant technology. The definition of the perceived performance mix can be stated as followed:

The perceived performance mix is the mix of functional attributes from a technology as appeared valuable by customers.

2.1.2.3.2 Envelope Curve

A combination of multiple S-curves is called an Envelope Curve and indicates the technological evolution over time. This Envelope Curve could be used as a simple (although hardly accurate) method of long term forecasting as stated already by Ayres [RD 4]. Figure 2-6 shows this enveloping curve with an example of the portable music player market. Additionally the difference in radical and DTs is illustrated. The dotted arrows represent the demand increase of customers over time, while the black arrows represent a change in perceived performance over time.

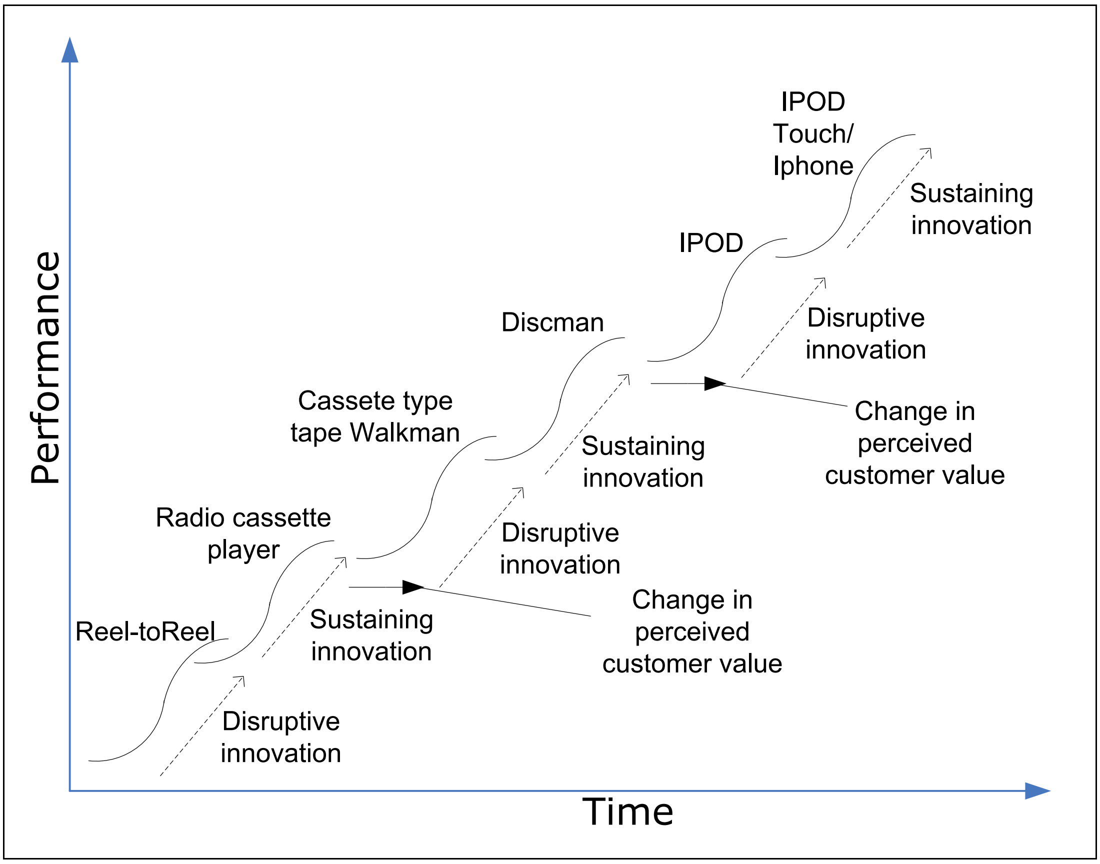

Figure 2-6: Envelope curve in the case of portable music players.

2.1.3 Disruptive Technology

Over the last few years the term Disruptive Technology has become a buzzword in several organizations around the world. The usage of the term, first introduced by Bower & Christensen [RD 1], has grown to a point where a lot of people have different definitions for it. Christensen [RD 20] also added to this ambiguity of the word by renaming his DTs into disruptive innovations. Because of the focus on space technologies within this research, the term Disruptive Space Technologies will be used. This work package will elaborate what the theory of DTs is, according to Christensen [RD 20] & Adner [RD 21], and how these views differ from the innovation theory discussed before. After that the definition of DSTs will be given, with an elaboration of the differences to the business literature in innovation and the differences in market dynamics.

2.1.3.1 Theory of Disruptive Technologies

A DT is an exception to the radical / incremental innovations theory, which Christensen [RD 22] classifies as sustaining innovations, because companies marketing these radical / incremental innovations continue serving the same customers with the intention to sustain their position in the market. An opposite of these sustaining innovations are DTs, which are technologies that disrupt the market of existing technologies exploited by incumbent companies. In practical terms this means that incumbent companies exploiting a dominant technology are being disrupted by new entrants exploiting a new technology [RD 23]. Also supporting this is a quote from Tellis [RD 24]: "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 [redirect] assets to serve that market." Compared to the innovations in the previous paragraphs DTs are therefore based on the disruptions of actors on the market and not only on products or services.

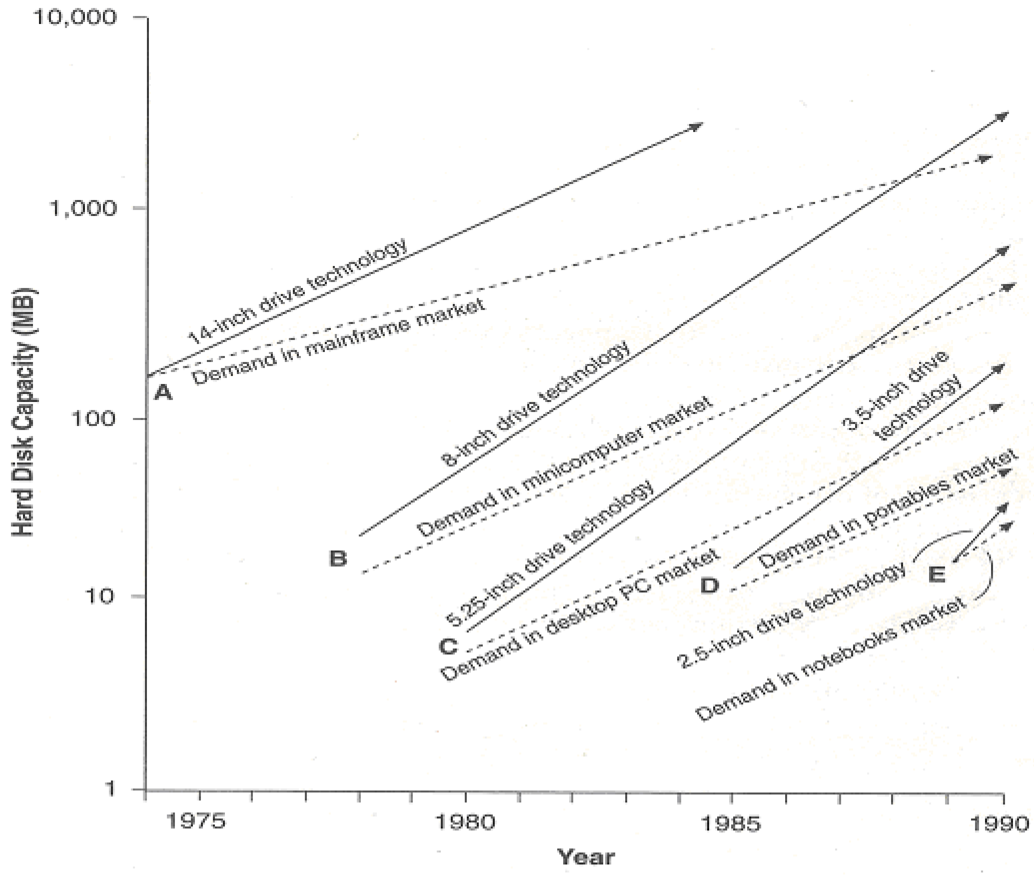

Figure 2-7: Christensen's [RD 25] example of DTs in the hard drive industry.

The DT does not always have to be technologically superior in comparison to the dominant technology in the market. On the contrary, such DTs are often initially simpler and cheaper compared to the dominant technologies. They do however perform better on an alternate perceived performance mix of customers who do not make up the mainstream market. This perceived performance mix could have a unique attribute like increased focus on lower costs, an increased ease of use, a new feature, higher flexibility, shorter development time etc. Because of this technological inferiority and differences in perceived performance mix, incumbent companies are blind sighted against the potential of the technology. They believe that the new technology can only serve a niche market and that the majority of their customers will not value its use (in fact often their customers tell the incumbent that they do not value the new features [RD 25]).

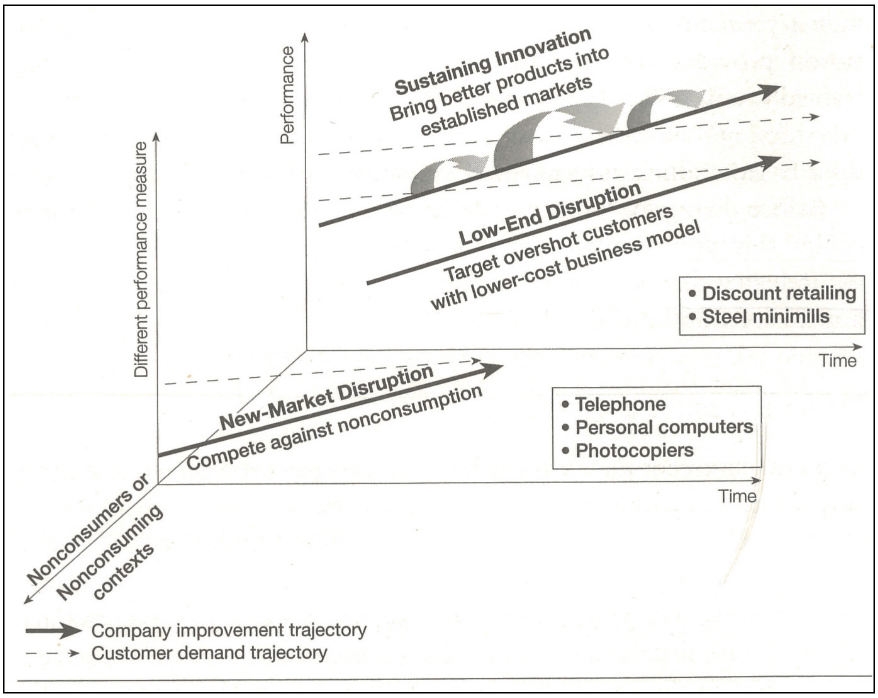

Figure 2-8: Christensen's [RD 26] example of DTs over performing in different ways.

A new technology becomes disrupting, when in addition to serving a niche market in the beginning, it starts to appeal to the majority of customers in the mainstream market. Christensen [RD 26] calls this process low-end disruption and illustrates this by the graph in Figure 2-8. This event occurs because the DT, through incremental innovations, starts to deliver the same or better performance than the previously dominant technology, while also having the special attribute which was valued by the niche market. When this happens, the new technology rapidly becomes the new standard, the old technology and the incumbents that exploited it are being pushed out of the market.

Table 2-1: Examples of Disruptive Technologies.

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

Non-space related examples of incumbents disrupted by new entrants are illustrated in the Table 2-1. The table shows the dominant technology, the incumbent marketing the technology, the DT, the new entrant marketing the DT and the disruptive attribute which is the biggest source of change in perceived customer value that sparked the disruption.

2.1.3.2 Theory of Disruptive Technologies by Adner

When a technology emerges, the technology is valued by the customers mainly on its most critical performance value [RD 21]. Over time however, when the initial basic functionality or functional threshold is reached, the perceived performance mix of the technology starts to change. This is because, even though a customer still appreciates a performance gain on the critical performance, they do not want to make concessions to other performance attributes like cost. Therefore, customers do not want to pay for something they do not need; the mainstream market divides itself into different market niches which value different aspects of performance. Adner [RD 21] explains this by taking an example of out of the microprocessor industry and compares the Pentium processors to the Celeron processors. He states that even though the Celerons are technological inferior to the Pentiums, the Celeron was and still is very successful because it targets a market segment which values low cost more than high technical performance. This is also described by Adner [RD 21] as an example of a DT. Each performance attribute is valued differently according to the customers in the corresponding market niche. This process can be illustrated by the value trajectory, which is a two-dimensional representation of the perceived performance mix, in Figure 2-9. The graph shows the value trajectory of a market segment which passes through several indifference curves. The indifference curve is a level of performance needed of a functional attribute by a customer. It has three levels; low-, medium- and high-end market segments. In support of this, Christensen [RD 22], also states that customers are initially focusing on functionality and reliability before focusing on cost.

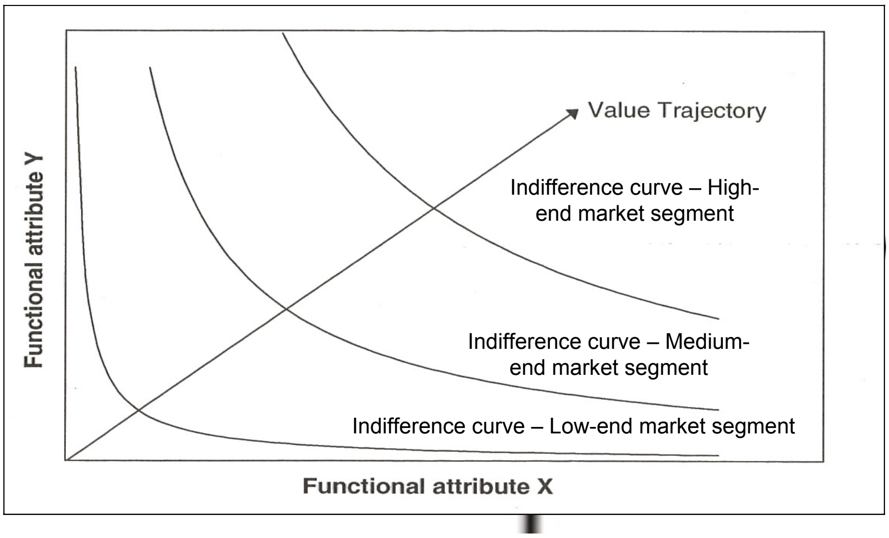

Figure 2-9: Indifference curves and a value trajectory from Adner [RD 21].

Figure 2-10 shows an example of the value trajectory of a personal computer (PC) and a personal digital assistant (PDA). As can be seen, customers of a PDA technology are quickly satisfied with a low storage capacity while the portability attribute is valued much higher. The customers of the PC technology have an alternate perceived performance mix and value storage capacity higher than portability.

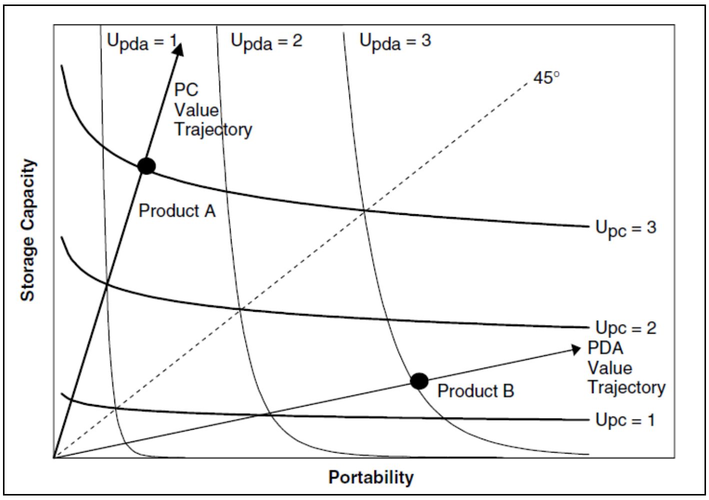

Figure 2-10: Different value trajectories [RD 21].

Other examples that have a value trajectory and indifference curves in this graph are netbooks, laptops and tablet PCs. The phenomenon of changing value trajectories or changing perceived performance can also occur within one technology domain. For example automobiles were first primarily valued on speed, after which aesthetics, functionality and safety became more important attributes, creating an indifference of most customers to maximum speed.

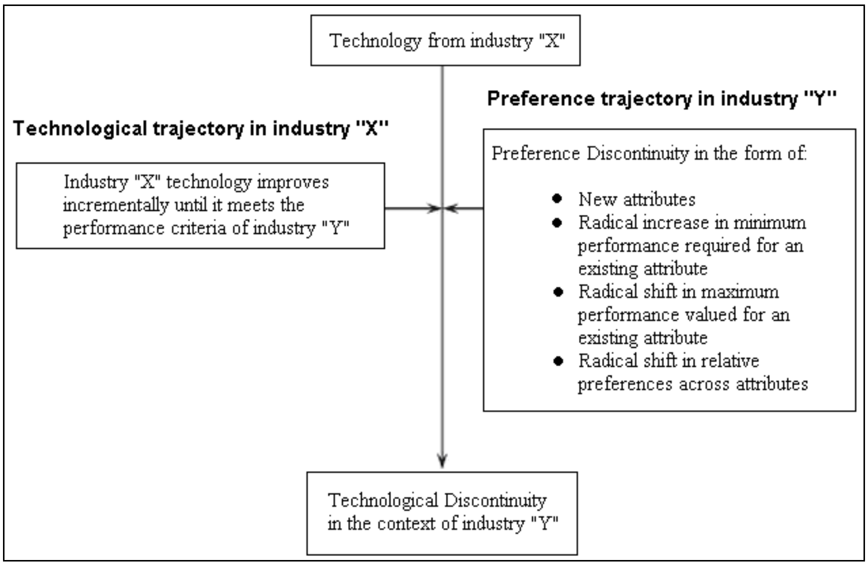

Figure 2-11: An integrated model of technological transitions: the role of preference discontinuities [RD 27].

With respect to space, the first rockets were measured on capabilities like range and payload mass while later reliability, safety and especially costs became more important. Christensen [RD 26] also supports this by claiming that technologies after reaching a basic level of functionality and performance are being measured on cost and flexibility (although this point differs in segments of the market).

When a value trajectory or perceived performance mix changes, the technology from one market niche can migrate to another and eventually push the dominant technology in this market out. This is the basis of the DTs theory. This process is also shown in Figure 2-11.

For space, this means that the perceived performance mix is determined by an evolutionary process over time. This concept is supported by the fact that in the beginning of the space age, the technical performance was highly important while later economic aspects became relatively more important. In which way performance is valued in the future depends highly on politics and policies concerning the space sector.

2.1.3.3 History and Critique on the Theory

The theory results from the original concept of creative destruction of Schumpeter [RD 28], although differs in the fact that it initially focuses on an alternate market segment and from this position, encroaches on the dominant market. Over time, Christensen has altered (or as he describes it, matured) his theory, to encompass all disruptive innovations. This means that not only technologies but also processes, paradigms and position innovations are allowed to be disruptive. One of the biggest opponents of this change is Markides [RD 29]. He states that broadening the concept is a mistake because different kinds of innovations have different competitive effects and produce different kinds of markets. Like Markides, other researchers have posed questions on the theory of DTs as well. Some examples are listed below:

- How can the theory be used as a predictive tool? [RD 24]
- Is a technology inherently disruptive, or does disruptiveness depend on the perspective of the firms confronted with the technical change? [RD 30]
- What is the exact definition of a DT? [RD 31]
- The theory names the creation of spin-offs as a solution to deal with DTs. What and when should this be done? [RD 31]
- When is a DT disrupting a dominant technology? [RD 31]
- The theory is based on inadequate empirical data [RD 32]
- Can the theory be used for creating instead of identifying DTs? [RD 33]

These gaps in the theory have become known to the researchers working in this field and many have made attempts to fill these gaps. Some examples are listed below:

- Paap & Katz [RD 34] utilizes the theory of S-Curves as a method to model the underlying factors influencing disruptive innovations.
- Govindarajan & Kopalle [RD 35] propose a method to measure the disruptiveness of innovations
- Christensen [RD 36] explains a method which can be used to seeing the next disruptive innovations on the horizon.
- Drew [RD 37] uses scenario planning methods to identify disruptive innovations at an early stage.
- Adner [RD 38] proposes a method to identify how the customers perceived performance changes as a technology evolves. It uses this method as indicators for new disruptive

threats.

- Sainio & Puumalainen [RD 39] have devised a method to measure the disruptive potential of a new technology
- Sood & Tellis [RD 32] have created a model for understanding and predicting Disruptive Technologies

Most researchers are focusing on the predictability of DTs as this would be the most beneficial to companies dealing with a potential disruption. However, no consensus has been reached so far on what a DTs precisely is and how that can be predicted. In fact to date, no evidence of any method accurately identifying or predicting the course of the disruption of a technology has been found. It seems that the theory is suffering from a too broad spectrum of situations classified as disruptions as well as the problem of creating a unified theory which is capable of describing disruption in a range of markets with different market dynamics.

Because of this, researchers have begun to adapt the general theory of disruption to specialized fields like education [RD 40], medicine [RD 41] and the space sector [RD 42][RD 43]. These fields have adopted a customized view of how disruptive technologies diffuse according to their unique market dynamics. This research mainly focuses on the theory creation and prediction of DTs in the space sector.

2.1.4 Summary

To summarize DTs according to Christensen [RD 25] we will use several articles that provide a description of the theory. The main characteristics of a Disruptive Technology (DT), according to Adner [RD 21], Gilbert [RD 44], Tripas [RD 27] and Govindarajan & Kopalle [RD 35] are:

- DTs serve a different market segment than the dominant technology either because they serve:
  - a niche-market (part of the market with different requirements)
  - a low-end market (part of the market where customers have a lower willingness to pay)
  - a high-end market (part of the market where customers have a higher willingness to pay)
  - a fringe-market (a market which is similar to the main market).
- Often, at the moment of entrance in the market, DTs have a worse performance compared to the dominant technology in the dominant main performance attribute (for example: sound quality in the disruption of Discmans by MP3 players). This leads to an under appreciation by the incumbents of the technology and in this way opens up the way for new entrants. When the DT starts maturing, it surpasses the dominant technology by fulfilling the customer needs better because of alternate mix of performance attributes.

From the before mentioned insights the following definition of DT 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 performance mix, which is valued more by the customer than the one of the dominant technology.

2.2 Analysis of Space Sector Infrastructure

In this chapter the path of a technology through various development stages and the development procedures are described. Market properties and barriers are elaborated to provide an overview of the landscape and administrative procedures of technology development in the space sector.

2.2.1 Space Sector

Since its creation roughly sixty years ago, the space sector has relied heavily on governmental contribution for the majority of its funding (with an exception of telecommunications market). In this, the space sector is somewhat of an anomaly as other historically high tech industries like the railroads industry, the telecommunications industry, the aircraft industry and computer industry all required an initial government investment before it was feasible for the private commercial sector to take over. The space sector has not gone through this milestone yet, but has a potential to do so, if it starts investing in the development of DSTs. These technologies can potentially decrease costs, increase responsiveness and improve the performance of space technologies, making them more attractive for commercial ventures. Investments in breakthrough technologies, which category DSTs are part of, have decreased since the major successes in the late 60s and beginning 70s. From this moment on, budgets were cut and investment decision makers started to focus on 'safe' investments in incremental innovations despite the clear benefits breakthrough technologies might have.

The space sector is a complex market which is highly influenced by governmental entities. Spread over the world, there are over 50 space agencies (e.g. NASA, ESA, JAXA, Roskosmos) more than 40 commercial operators and several institutional entities (e.g. NOAA, EUMETSAT, JME, EC) which are procuring satellites and satellite data. In addition, there are more than 15 satellite integrators. European companies sell to actors worldwide: more than 40% of activity is for commercial entities or entities outside of Europe. This makes the European space sector as a whole compete with the United States, Russia, Japan and more recently with India, China and Brazil. In order to remain competitive in light of this upcoming competition, the European space sector will continuously have to innovate to improve its existing capabilities and prepare for future developments. One method of doing this is by selecting technologies with the highest potential for disruptiveness for development.

2.2.2 Innovation Dynamics of the Space Sector

These influences on technology development in the space sector can be categorized according to two categories, the technological characteristics and the market factors. These two will be elaborated in the next two sections.

2.2.2.1 Technological Characteristics

Space is an especially harsh environment which is firstly hard to reach and secondly hard for technologies to operate in. This creates unique constraints in form of performance levels exceeding those required for terrestrial technologies. Performance requirements unique for space technologies include resistance to:

- Extreme temperatures
- Large and frequent temperature variation
- Micro impacts
- Vacuum
- Limited capabilities to repair or perform adjustments after deployment
- Shocks and high g-forces (during launch & reentry)

Additionally, the high costs and risks involved with moving objects into space results into:

- o High quality and flight heritage (technology has proven itself as reliable for operating in space) requirements
- o High testing costs and long testing times
- o High costs and fewer applications

These factors result in a vicious circle of higher costs and testing times within the space sector:

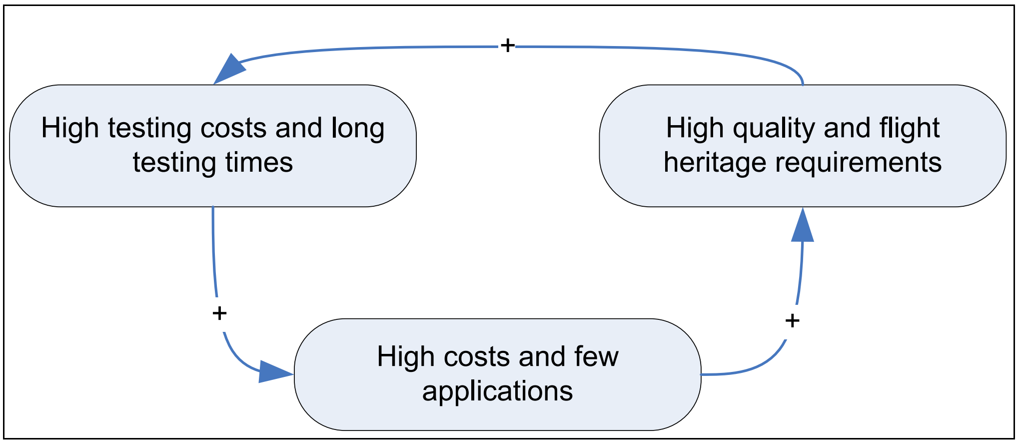

Figure 2-12: Vicious circle of space technology cost.

Figure 2-12 illustrates how the high quality requirements of space technologies lead to high costs and flight heritage requirements, which lead to high testing costs and long testing times which in turn again lead to high costs and relative few applications. This is also evident by the decrease in orbital launches illustrated in Figure 2-13.

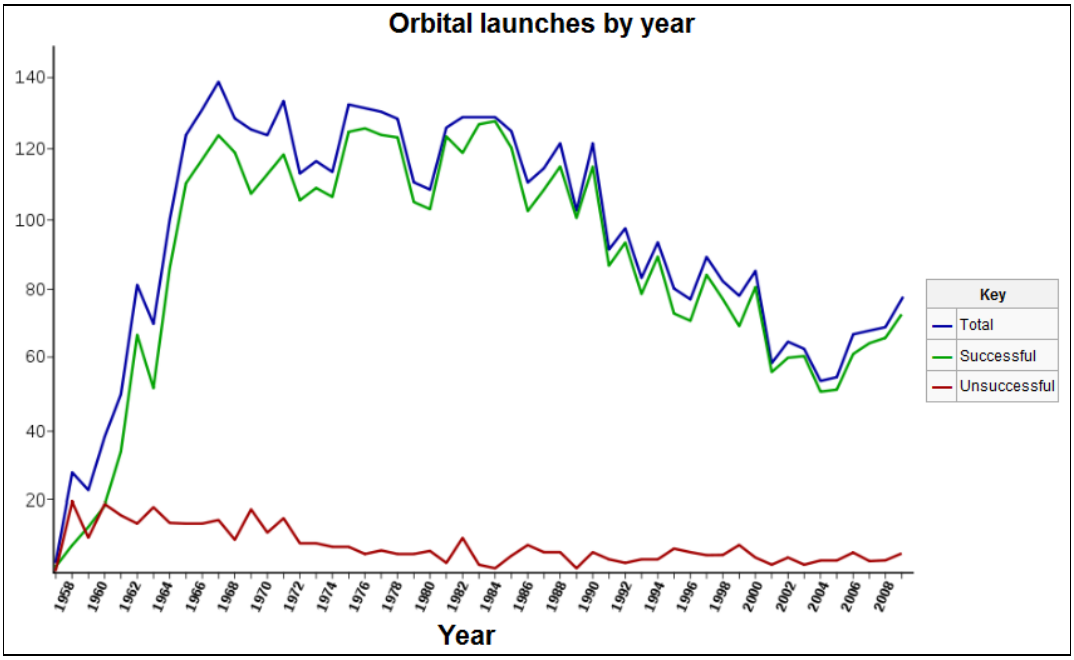

Figure 2-13: Number of recorded spacecraft launches per year (Wiki, 2010).

Despite this vicious circle, innovation does occur within the space sector. This is mostly due to several innovation enablers, which are programs which are investing in the development of technology. An extensive analysis was made of the historical evolution of performance within space systems at the DLR in Bremen. It concluded that some trends can be observed within the evolution of space systems. An example of an observed trend is illustrated in Figure 2-14.

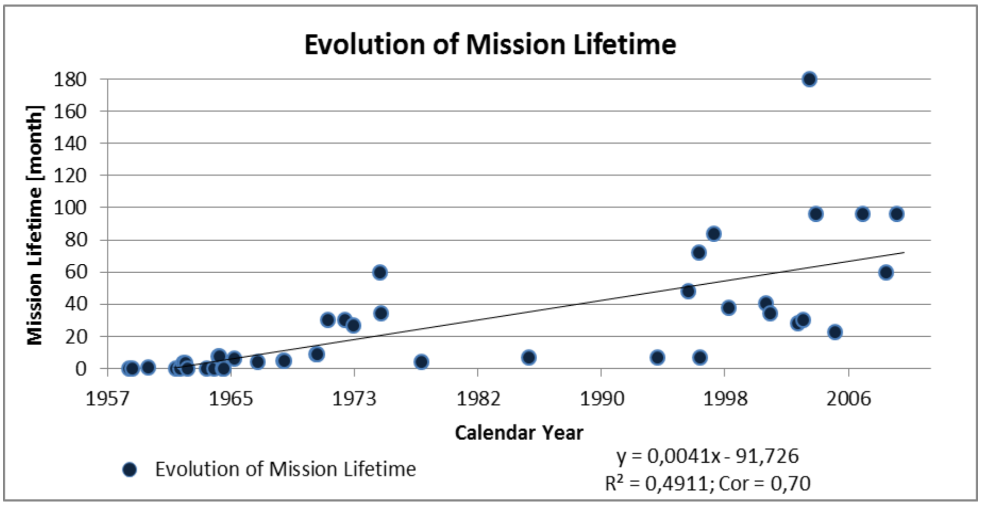

Figure 2-14 Evolution of mission lifetime of exploration systems from 1958 to 2010.

More results of these analyses can be found in Stellmann et. al [RD 45].

2.2.2.2 Market Factors

The space sector can generally be divided into two fields, the military and civil. The civil field is divided again into a commercial and scientific field. The military and scientific fields receive the majority of their funding from governmental instantiations. The commercial field however, has citizens and companies as direct customers and receives money through them as well as occasional extra funding from governmental instantiations. This also means that the innovation dynamics in the scientific and military field differs from the commercial field and is caused by a different customer seller relationship. In general the following market types can be identified:

1. Mass market — Many sellers face many buyers
2. Monopoly market — One seller which faces multiple buyers
3. Monopsony market — One buyer which faces multiple sellers
4. Oligopoly market — Few sellers who face multiple buyers
5. Oligopsony market — Few buyers who face multiple sellers

Szajnfarber & Weigel [RD 46] have analyzed the innovation dynamics of the space sector with a special focus on ESA science missions, thus the scientific field is discussed earlier. Their conclusion was that the scientific field has a monopolistic-oligopolistic market structure dominated by governmental acquisition. This market structure entails that a monopsonistic buyer, which in the space sector is a governmental institution, faces oligopolists, which in the space sector are prime contractors. These sellers in turn are in an oligopsonistic market structure as a few primes face a high number of suppliers. The difference between this market structure and a more traditional market structure is illustrated in Figure 2-15. This figure shows the buy-side and sell-side with their transaction area. As can be seen, the buy side of the space sector in the science field is clearly monoponistic while the sell side is oligopolistic.

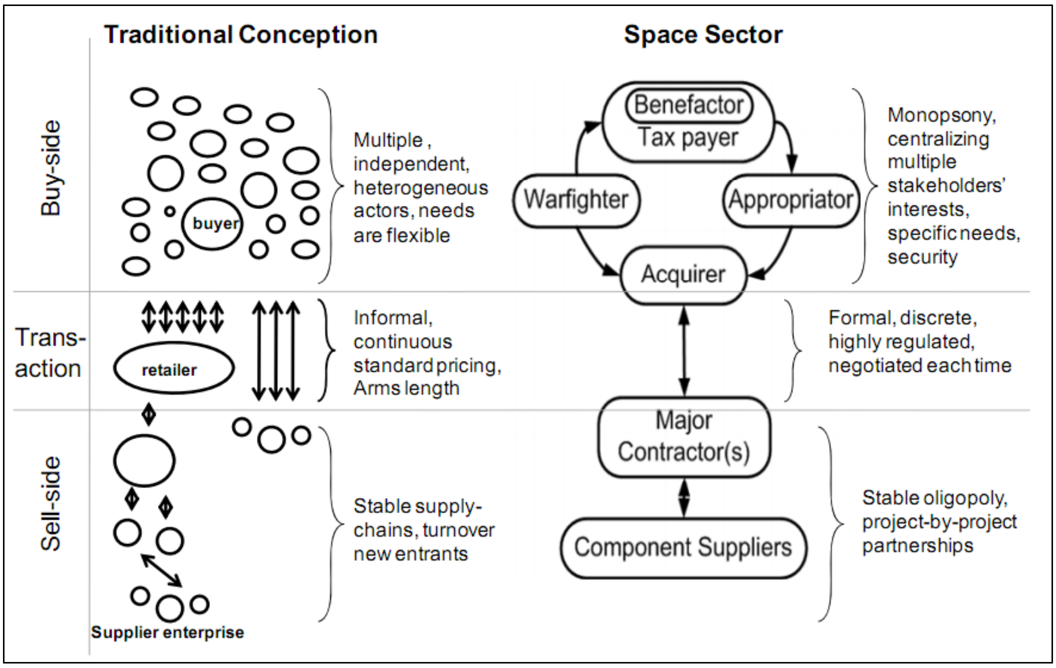

Figure 2-15: Difference between customer-seller interactions of the space and non-space sector in case of science missions [RD 47].

After an in-depth analysis of the space sector, it was found that even though the military and scientific space sector in Europe is dominated by governmental acquisition, this is hardly a monopsony. This is caused by the high number of space agencies (18 ESA participants, 1 associate member and 12 cooperative members in Europe and over 50 governmental agencies worldwide).

Because of this, the innovation dynamics of the space sector are altogether different, although the governmental influence is still strong. This strong influence is evident by the fact that governments tend to favor national industry versus foreign industry in order to get an industrial return on their space investments. This means that even though national industry has the potential of multiple buyers, it gets a large share of its orders either directly or indirectly (in the case of Europe through ESA or the EC) from national governments. Nonetheless orders from other nations are also common, as more than 40% of activity is for commercial entities or entities outside of Europe. This is mainly caused by a sharing of knowledge and capabilities over the different space capable nations. Because of this, the space sector is viewed as a complex highly governmentally influenced market rather than a monopsony-oligopolistic market.

In the space sector a difference can be made between basic technology development and mission specific technology development. When looking through the "technology push" and "demand pull" model, the 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). Especially push investments result in breakthrough technologies while the pull investments result in more incremental innovations [RD 48][RD 49]. Because of this, the push area is especially appropriate when looking for DSTs. The different market factors with their push and pull areas have been summarized in Figure 2-16.

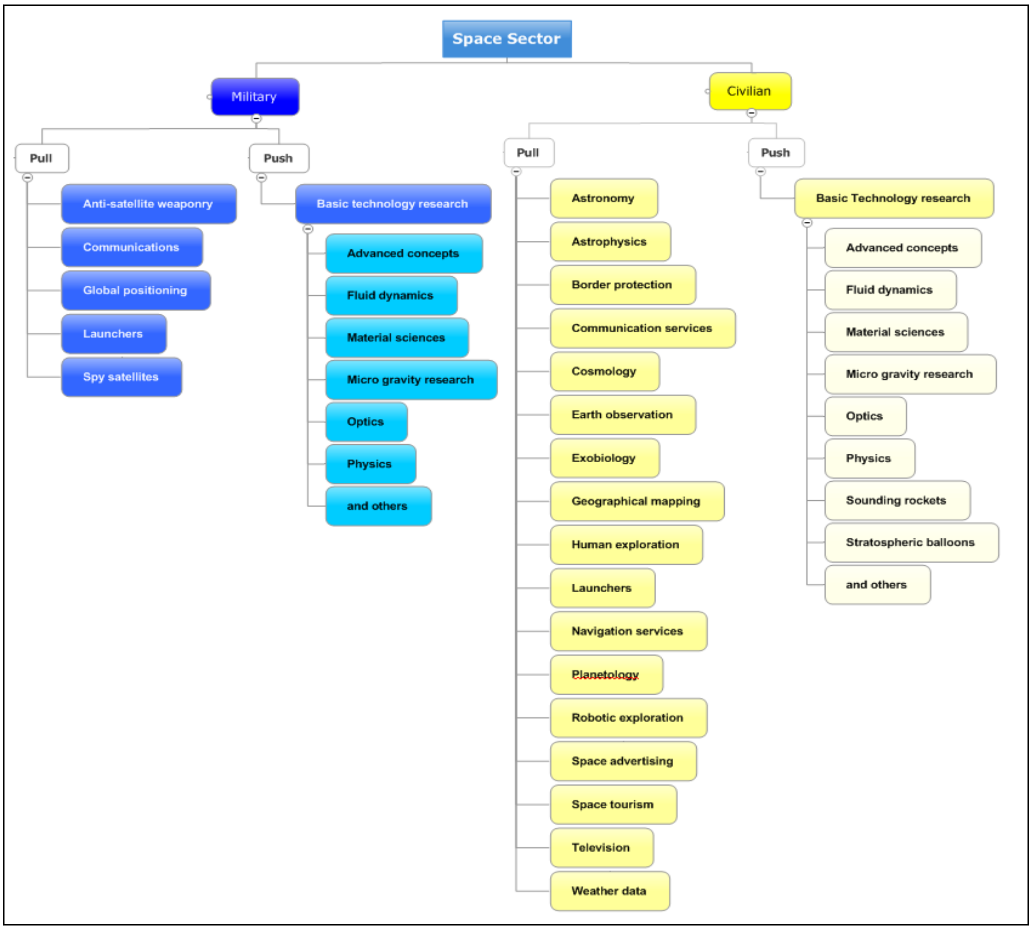

Figure 2-16: Space sector infrastructure.

2.2.3 R&D Infrastructures of the European Instantiations

In this paragraph the technology development structure within the European space sector will be elaborated. As stated before the European Space Sector is a complex market highly controlled by governmental instantiations. This means the development of technology is centralized around governmental institutions. For the European space sector, these institutions are divided by a national level, a European level and an intergovernmental level.

The national level is represented by the government of each space capable nation. In Europe these governments cooperate within the European Space Agency (ESA). They decide by themselves which programs of ESA will be supported by them in addition to which national projects will be initiated.

The European level is represented by the European Union, which funds technology development which is important for the capabilities of Europe through its framework programs. The European Union is funded through each of its member states (not necessarily member of ESA).

The intergovernmental level, which has high overlap with the European level, is represented by ESA. ESA receives money from its members (not necessarily members of the European Union) to fulfill its programs. Every member state can choose whether to invest into a program or not (although there are mandatory programs). It does this under a principle of geographical return which means that the money contributed by each member state will be fairly distributed back to the state in the form of research money. ESA has an extensive technology development strategy, which covers both basic technology research (push) as well as program specific development (pull).

To comply with the ends of this strategy, ESA has five generic technology programs which aim to support technology development from low to medium TRL levels:

- Basic Technology Research Programme (TRP)
- General Support Technology Programme (GSTP)
- Technology Transfer Programme (TTP)
- European Components Initiative (ECI)
- On-orbit demonstration platform (Proba),

In addition, ESA has seven domain specific technology programs:

- Earth Observation Envelope Programme (EOEP)
- Advanced Research in Telecommunications Systems (ARTES)
- Global Navigation Satellite System (GNSS) evolution
- Transportation, Human Exploration
- Science Core Technology Programme (CTP)
- Mars Robotic Exploration Preparation Programme (MREP)
- Future Launchers Preparatory Programme (FLPP).

These programs and the Technology Readiness Levels (TRL) they cover are shown in Figure 2-17. Additionally in the before mentioned picture, it has to be noted that there are mandatory programs and optional programs. This means that member states of ESA are either obliged to participate in a program or can optionally choose which programs to participate in. The mandatory programs are TRP and CTP while the rest are optional programs.

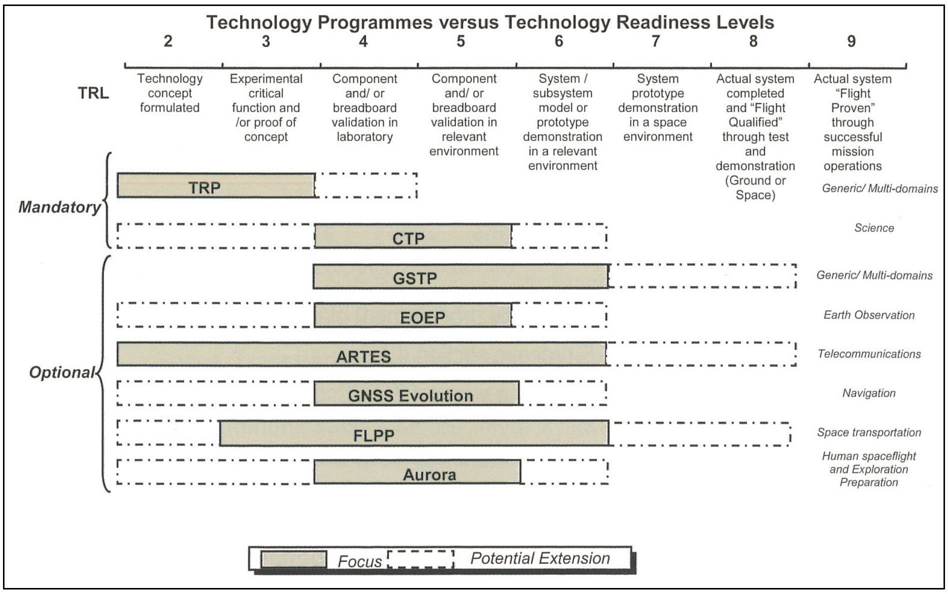

Figure 2-17: ESA technology programs and Technical Readiness Levels (RTL) scale (ESTMP, 2008).

The transfer of technologies from the mandatory program to the optional programs is difficult. This often leads to a Death Valley between TRL levels 4-6 (also called The Chasm by Moore, [RD 50]), which inhibits the development of technology. This Death Valley is also shown in Figure 2-18.

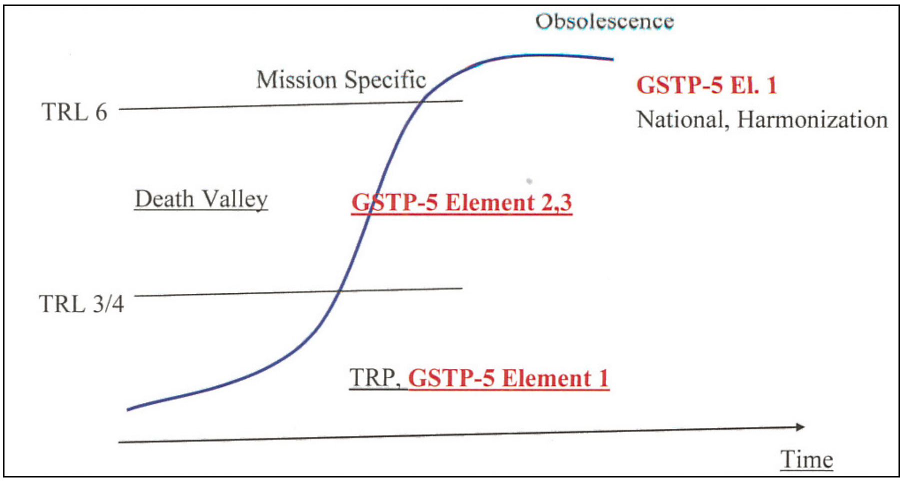

Figure 2-18: S-Curve of space technologies with TRL levels and Death Valley (ETSLTP, 2009).

2.3 R&D Key Player Analysis

The goal of this work package is to map the different entities of potential DST key players in several fields of high technology. The European Space Policy Institute Report 24 from July 2010 [RD 51] has been used to define the fields of research:

- Photonics (usage of light/ optical technology for various applications like communication and measuring)
- Advanced Materials (lightweight materials, fibers, composites)
- Micro- and Nanoelectronics
- Biotechnology
- Information and Communication Technologies
- Robotics

From the before mentioned report, several online portals of professional associations have been used for a survey of potential key player candidates. These have been added to the portals already found, to create the list in

Table 2-2.

Once an entity has been identified, further review has been undertaken by e.g. surveying online articles, news articles or general information. Criteria for selection e.g. have been amount of funding in relation to other competitors, prominence in media and scientific journals and product contributions to the market.

Table 2-2: Survey sources for each survey domain.

Domain	Portals/ Associations
Photonics	http://www.photonics21.org
Advanced Materials	http://eumat.eu
Micro- and Nanoelectronics	http://www.eniac.eu
Biotechnology	http://www.suschem.org http://www.biofuelstp.eu http://europabio.org
Information and Communication Technologies	http://www.networks-etp.eu http://www.artemisia-association.org
Robotics	http:// www.robotics-platform.eu

2.3.1 Survey Results

This chapter lists the results of the key player survey, executed as described above. The results are sorted by domain.

2.3.1.1 Photonics

Table 2-3: Key players for the Photonics domain.

Entity	Website	Type	Field of Work/ Research
Carl Zeiss AG	www.zeiss.de	Company	Spectral sensors, microscopy, industrial lenses, general lenses and spectrometers
Ericsson	http://ericsson.com	Company	Dense wavelength division multiplexing, optical transport network
Alcatel Lucent	http://www.alcatel-lucent.com/	Company	Wireless and wireline broadband access, packet and optical networking, network security and optimization
Siemens AG	www.siemens.com	Company	Optical network systems
Toshiba	http://www.toshiba.co.jp/worldwide/	Company	Optical disc drivers
Q-Cells	http://www.q-cells.com/	Company	Solar cells
Solon SE	http://www.solon.com/	Company	Solar cells
Diehl BGT	http://www.diehl-bgt-defence.de/	Company	Infrared and night vision systems, modeling, design, assessment, development as well as integration and measurement of seeker heads with image-generating, optical sensors in various spectral ranges for missiles and, with increasing significance, also for reconnaissance and warning systems
BAE Systems	www.baesystems.com	Company	Command, Control, Communications, Computing, Intelligence, Surveillance and Reconnaissance
Qioptic	http://www.qioptiq.com/	Company	Optical components, glass, infrared sensors
Photonis	www.photonis.com	Company	Low light level detectors, infrared and night vision

2.3.1.2 Advanced Materials

Table 2-4: Key players for the Advanced Materials domain.

Entity	Website	Type	Field of Work/ Research
Cranfield Energy Technology Center	http://www.cranfield.ac.uk/sas/aboutus/staff/oakeyj.html	University	Batteries
Metso Materials Technology	www.metsomaterialstechnology.com	Company	Monolithic components, multi material structures, metal matrix composites
Institute of Material Research (Tohoku University)	http://www.imr.tohoku.ac.jp/eng/	University	Materials properties and design, materials processing
MERL	http://www.merl-ltd.co.uk/	Company	New materials for extreme environments, polymers, composites, intermetallics
UMICORE	www.umicore.com	Company	Energy materials, performance materials, recycling
Bayer Material Science	http://www.bayermaterialscience.de/internet/global_portal_cms.nsf/id/home_de	Company	High-tech polymer materials and energy-saving lightweight solutions including carbon nano-technology, innovative adhesives, lightweight polyurethane foams and extremely thin, unbreakable polycarbonate films
ONERA	http://www.onera.fr/	Public Research Centre	Composite and metallic materials
IBM	http://www.research.ibm.com/nanoscience/nanotubes.html	Company	Carbon nanotubes

2.3.1.3 Micro- and Nanoelectronics

Table 2-5: Key players for the Micro- and Nanoelectronics domain.

Entity	Website	Type	Field of Work/ Research
IQE	iqep.com	Company	High Performance Concentrated Photovoltaic Solar Cells, MEMS materials, UHB LED Templates, High Speed > 25Gbs VCSELS

Technological Educational Institute of Crete	teicrete.gr	University	Organic electronics, TCOs, field emission, photovoltaic, self-organizing nanotubes
IFW Dresden	http://www.ifw-dresden.de/institutes/iff/research/Carbon/molecular-nanostructures	Public Research Centre	Nanomaterials, Graphene, aberration corrected electron microscopy, electron beam engineering, functionalization
Consiglio Nazionale delle Ricerche - Istituto per la Microelettronica e Microsistemi	http://www.imm.cnr.it/en	Public Research Centre	Materials and processing for sub-32 nm CMOS and non volatile memory technologies; materials, processes and devices for advanced power electronics; large area and plastic-based electronics; novel photovoltaic applications
IRIDA LABS Ltd.	http://www.iridalabs.gr/	Company	Analog and Mixed Signal VLSI Circuits, Digital VLSI, Instrumentation Microelectronics, Signal Processing, Image Processing, Information Fusion, Sensors
CNR-IMM Roma	http://www.artov.imm.cnr.it/	Public Research Centre	RF MEMS, Microwave Magnetics, Electromagnetic Band-Gap Structures, Metamaterial Circuits
Fraunhofer Group Microelectronic	http://www.mikroelektronik.fraunhofer.de/en/welcome.html	Public Research Centre	Development of CMOS, smart system integration, communication technologies, ambient assisted living, energy efficient systems and e-mobility, light, safety and security, entertainment
Fraunhofer Nanotechnology Alliance	http://www.nano.fraunhofer.de/english/index.html	Public Research Centre	Nano-materials, nano-particles, thinfilms, nano-optics, nano-biotechnology, modeling, tools, production technologies
CEA	http://www.cea.fr/	Public Research Centre	Miniaturization, Microsystems

2.3.1.4 Biotechnology

Table 2-6: Key players for the Biotechnology domain.

Entity	Website	Type	Field of Work/ Research
Technische Universität Graz	http://www.tugraz.at/	University	Biocatalysts, biomechanics, bioengineering
Commissariat à l'Energie Atomique – Life Science and Technology Research Institute	http://www.cea.fr	Public Research Centre	Molecular biology, biochemistry, basic research
Tornier	http://www.tornier.com	Company	Artificial joints
Roche	http://www.roche.com	Company	Pharmaceutics, diagnostics

2.3.1.5 Information and Communication Technologies

Table 2-7: Key players for the Information and Communication Technologies domain.

Entity	Website	Type	Field of Work/ Research
STMicroelectronics	www.st.com	Company	Semiconductors, power management, integrated devices
Dassault Systemes	http://www.3ds.com/	Company	Simulation and design software
TIVIT Ltd.	http://www.tivit.fi/en/		Next media, cloud software, cooperative traffic, devices and interoperability ecosystem, flexible services, future internet
WLAB	http://www.w-lab.it/	Company	Gaming, location, security, W-Lan, Bluetooth
ABB AB	http://www.abb.com/	Company	Industrial robots, automation
Siemens Corporate Research	http://www.siemens.com/innovation/en/	Company	Cloud computing, content management
Nokia Research Center	http://research.nokia.com/	Company	Sensing and data intelligence, user interfaces
Microsoft: European Microsoft Innovation Center GmbH	http://research.microsoft.com/en-us/labs/emic/	Company	Cloud computing, automation, knowledge management, privacy protection
Centre for Telematics and Information Technology	http://www.utwente.nl/research/ctit	University	Wireless sensor systems, embedded systems

2.3.1.6 Robotics

Table 2-8: Key players for the Robotics domain.

Entity	Website	Type	Field of Work/ Research
Institute of Robotics and Intelligent Systems	http://www.iris.ethz.ch/	University	Micro- and nanorobotics, bio-inspired robotics
Deutsches Forschungszentrum für Künstliche Intelligenz GmbH Robotics Innovation Centre	http://www.dfki.de/robotics	Public Research Centre	Search and rescue robotics
Technion Autonomous Systems Program	http://tasp.technion.ac.il/	Public Research Centre	UAV swarms, nano UAVs

2.4 Analysis of Conventional Space Technology Development

As already explained at the beginning of Chapter 2.2.2, the space sector can be divided into the military and civil fields. The different fields are subject to both push and pull factors. This means that governmental instantiations are main drivers of technological innovation. European governmental instantiations include the European commission, ESA, national agencies, national governments and regional governments. They support space technology development either through providing funding for missions (pull) or for basic research (push). Although governmental instantiations are the monetary drivers for innovation, the bulk of actual technology development is done at research institutes, universities and companies. In the case of the commercial field however technologies are developed with a specific goal of serving a customer and technologies will be developed by a company according to the precise requirements of a customer. The following sections will explain in detail how technology is developed in the European space sector, which effects drive their development and what the differences between technology pull and technology push are.

2.4.1 Pathways of Push Technology Development

The development of a space technology starts with an idea; this idea can come from an individual or a group process. Mascitelli [RD 52], states that ideas for breakthrough innovations originate from the tacit knowledge of the inventor. This knowledge is build up from experience and allows the inventor to combine multiple disciplines resulting in a potentially breakthrough innovation. After an idea is worked out into more detail it becomes a concept. Provided the inventor has the possibility, time, money and motivation, he or she will start championing the invention. If not, another may pick up the concept and start championing it for the inventor. The innovation champion will promote his technology in the context of a research institute, university, governmental instantiation or a (new start up) company. Presumably new developments require investments in time for further development and this can be accomplished in several ways; investments through business angels, private-, academic- or governmental funding. These investments are enablers of innovation because they serve as funding which might be needed in the far future which would otherwise not be invested in. Some examples over governmental programs include:

ESA:

- Innovation Triangle Initiative (ITI) for funding for inventors by connecting them to technology developers and customers
- Ariadna by funding academics for doing advanced space technology research
- Network Partnering Initiative (NPI) for funding of PhD researchers

European Commission:

- Framework programs bring together all research-related EU initiatives under a common roof playing a crucial role in reaching the goals of growth, competitiveness and employment.

National agencies:

- Several, for example: DLR's Technology Marketing portal which funds concepts of advanced technologies.

Non-European example:

- NASA Game Changing Technology program supporting Crosscutting Capability Demonstrations

After working out the concept, the technology needs to be tested and eventually flight proven. This is the largest barrier for technology development and most technologies will be unable to cross this barrier, the before mentioned Death Valley in technology development (see Section 2.2.3). Testing of innovative technologies mostly occur within on-orbit technology demonstration programs like the Project for On-Board Autonomy (Proba) satellites. These programs create an artificial pull for innovative technologies.

2.4.2 Pathways of Pull Technology Development

If a technology is developed for a specific mission, it is also called a pull in technology development. During the initial evaluation (before mission details are determined), technological needs are determined along with an initial solution for these needs [RD 46]. Once the mission is chosen, scientific needs are translated into mission requirements which in turn raise the bar for the technological necessities [RD 46]. Overall the actual application of a new technology usually takes a long time from its initial inspiration [RD 53].

As the lion's share of technology developments are undertaken in the frame of a mission development (technology pull), the problem arises, that the selection of technology favors mature technologies. This creates the peculiarity of an impending dead-lock of technological development, because a certain technology is only developed if it is mature enough for a mission. This problem is even increased by the fact that as a result only missions are proposed that the scientists behind it already regard as technologically feasible, i.e. large gaps between technological state-of-the-art and technological mission demand are avoided [RD 54]. This can be a hindrance to innovation, as only sufficiently ambitious technological demands really drive innovation [RD 55].

Further difficulties arise due to the fact that technology is rarely matured within one project, but distributed over several ones. Consequently knowledge is lost during transfer from one project to the next, as usually the project teams differ and therefore lack the knowledge that has not been documented before. Additionally the longevity of each project can contribute to space engineers working only on a small number of projects during their career which decreases the willingness to be flexible with regard to Radical Innovations or DSTs. On the other hand the space sector tends to have well trained personnel, which sparks innovation due to different cultural background but at the same time it is also isolated from other industrial or technical areas [RD 53].

2.5 Disruptive Technologies for Space Applications

In the previous section the theory of Disruptive Technologies, the space sector infrastructure and the different pathways of space technology development we elaborates. Through insights gained in this chapter it was stated that the space sector is sufficiently different from mass market that it constitutes a reassessment of the theory of DTs and a creating of a new theory of DSTs.

This is done by using insights from the previous chapters combined with an analysis of five identified past DSTs. This analysis verifies which parts of the theory of DTs are applicable to the space sector and which are not. Results of this analysis will be valuable in identifying and evaluating DSTs.

2.5.1 Analysis of Past Technologies

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

2.5.1.1 Li-Ion and NiH2 Batteries

Batteries are used in satellites to cope with peak power demand and to maintain the satellite in times when the primary power supply (often solar cells) is not available. Historically, NiH_2 batteries (see Figure 2-19) were used in satellites but this technology has almost entirely been disrupted by Li-Ion batteries (see Figure 2-20). This disruption has been caused by the over-performance of Li-Ion batteries on some key performance attributes. The technologies differ both in active materials as well as basic cell design. These differences give both technologies different performance characteristics.

Figure 2-19: Block of NiH2 batteries [RD 56]

Figure 2-20: COTS Li-Ion battery [RD 57]

According to Wenige et al. [RD 58], the Li-Ion technology is sensitive to overcharge and over-discharge conditions. Therefore a sophisticated battery management system is mandatory. It should include, as a minimum, protection monitoring versus over-voltage and under-voltage as well as charge control. For highest charge cycle and life time expectations, it is strongly recommended to use cell balancing. Due to lighter material and higher energy density, Li-Ion batteries have lower mass and volume compared to the nickel based battery systems.

Besides the different performance characteristics of the active materials, the cell chemistry demands different approaches for the entire battery design, structure and interface. As NiH_2 is based upon a robust and stable chemistry, a simple battery design is sufficient. NiH_2 is not only able to bear deep discharge conditions but additionally it is insensitive against reverse current. Furthermore it is insensitive against over-charge. Its energy principle bases upon the production of internal pressure, which requires stable container material causing higher volume and mass of the entire system. Today NiH_2 is the system, where by far the most cycle life data and flight heritage are available. A summary of the differences between the technologies by Kopera [RD 59] & Schmiel [RD 56] is listed below:

NiH2 advantages:

- More charge cycles possible -> longer lifetime
- Overcharge possible
- Better fast charge abilities
- Higher Depth of Discharge (DoD) possible

Li-Ion advantages:

- Higher cell voltage (Compare Figure 2-21:)
- Higher specific energy (Compare Figure 2-21:)
- Higher energy density (Compare Figure 2-21:)
- Lower self-discharge (Li-Ion: 10%/month, NiH_2: 6-12%/day)
- Higher efficiency (Li-Ion: 80-95%, NiH_2: 70%)
- No memory effect

- Do not need high-pressure containers

Battery System	Negative Electrode	Positive Electrode	Electrolyte	Nominal Voltage (V)	Theoretical Specific Energy (Wh/kg)	Practical Specific Energy (Wh/kg)	Practical Energy Density (Wh/L)	Major Issues
Lead-Acid	Pb	PbO_2	H_2SO_4	2.0	252	35	70	Heavy, Low Cycle Life, Toxic Materials
Nickel Iron	Fe	NiOOH	KOH	1.2	313	45	60	Heavy, High Maintenance
Nickel Cadmium	Cd	NiOOH	KOH	1.2	244	50	75	Toxic materials, maintenance, cost
Nickel Hydrogen	H_2	NiOOH	KOH	1.2	434	55	60	Cost, High Pressure Hydrogen, Bulky
Nickel Metal Hydride	H (as MH)	NiOOH	KOH	1.2	278 – 800 (depends on MH)	70	170	Cost
Nickel Zinc	Zn	NiOOH	KOH	1.6	372	60	120	Low cycle life
Silver Zinc	Zn	AgO	KOH	1.9	524	100	180	Very expensive, limited life
Zinc Air	Zn	O_2	KOH	1.1	1320	110	80	Low Power, limited cycle life, bulky
Zinc Bromine	Zn	Bromine Complex	$ZnBr_2$	1.6	450	70	60	Low Power, hazardous components, bulky
Lithium Ion	Li	Li_xCoO_2	PC or DMC w/ $LiPF_6$	4.0	766	120	200	Safety Issues, Calendar Life, Cost
Sodium Sulfur	Na	S	Beta Alumina	2.0	792	100	>150	High Temperature Battery, Safety, Low Power Electrolyte
Sodium Nickel Chloride	Na	$NiCl_2$	Beta Alumina	2.5	787	90	>150	High Temperature Operation, Low Power

Figure 2-21: Properties of several types of batteries [RD 59].

History

The first experiments with Nickel Hydrogen batteries developed for space applications were conducted in the early 1970s [RD 60]. After this, the first experimental flights were undertaken in 1976/77 and the first commercial satellite flew in 1983 (Intelsat V-B) [RD 61]. After this Nickel Hydrogen batteries became the dominant technology for batteries in spacecraft until they were disrupted by Li-Ion and pushed into a niche market of mission with high cycle charge requirements.

First experiments with Li-Ion batteries started in the 80s, but it was not until 1991 that a first commercial version was launched by Sony [RD 62]. First commercialisation in space did not happen until 2004. From this period on Li-Ion batteries have begun replacing Nickel Hydrogen batteries, first only in GEO (orbit with low charge cycle requirements) but later increasingly in MEO and LEO through advancements in charge cycle requirement and thus lifetime. This increased the performance of Li-Ion batteries to the following performance attribute mix:

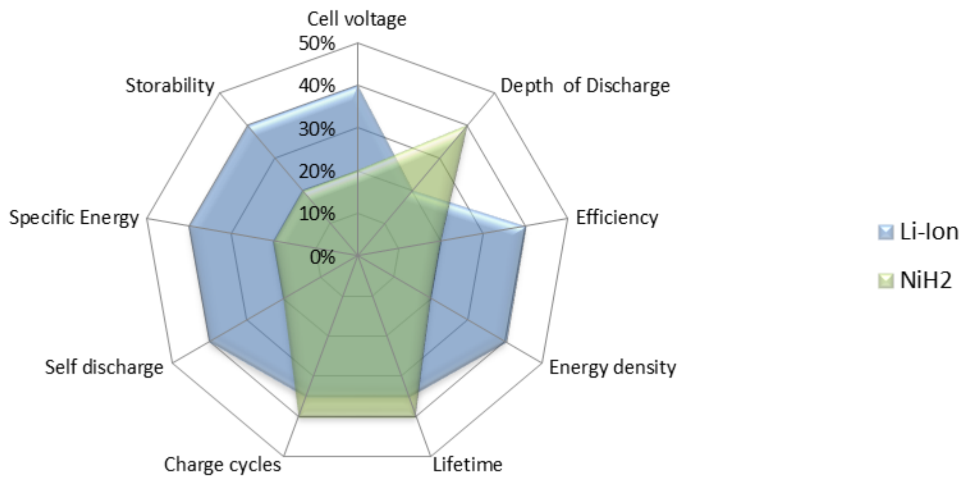

Figure 2-22: Performance attribute mix of Li-Ion and NiH_2 batteries.

This performance will continue to increase in the future through incremental innovations, eventually surpassing the performance of Nickel Hydrogen batteries.

2.5.1.2 GaAs and Silicon Solar Cells

Since the launch of Vanguard-I, the first solar-powered satellite, in 1958 [RD 63], solar cells have evolved to be the standard primary power source of Earth orbiting satellites and many exploration spacecraft.

A typical silicon based solar cell is depicted in Figure 2-23 and is based in the photovoltaic effect of semiconductors being hit by electromagnetic radiation and thus exchanging electrons between charge surplus (n-donator of the semiconductor) and charge absence (p-receptor).

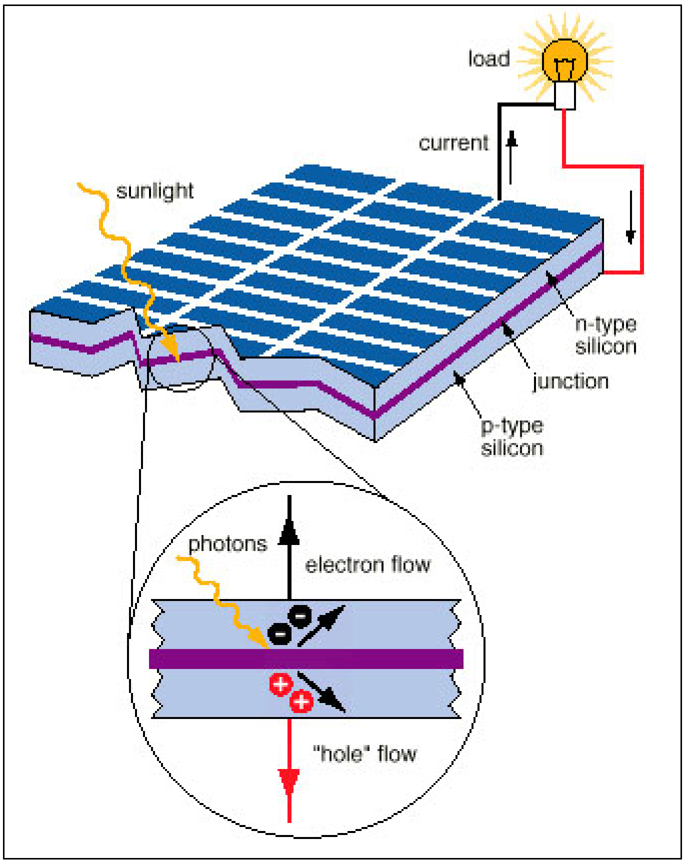

Figure 2-23: Scheme of the layers of a silicon solar cell [RD 64].

Depending on the actual semiconductor material, solar cells are sensitive to certain wavelengths of electromagnetic radiation, which allows the combination of various materials in layers to use a wider band of radiation (cf. Figure 2-24).

This lead to the usage of so called multi-junction cells, applying i.a. gallium arsenide as semiconductor, and thus attaining an increased exploitation of solar energy. This is one main advantage of GaAs multi-junction cells, the increased efficiency due to solar radiation. Additionally they are mostly insensitive to heat [RD 65].

Furthermore, the resistance against negative radiation effects is about 20% better than silicon based solar cells and the lifetime is also improved [RD 66].

Silicon is available in great abundance on Earth, which makes it a cheap resource, also because the refinement of silicon is inexpensive and reliable. Silicon cell efficiency is still of medium quality [RD 67].

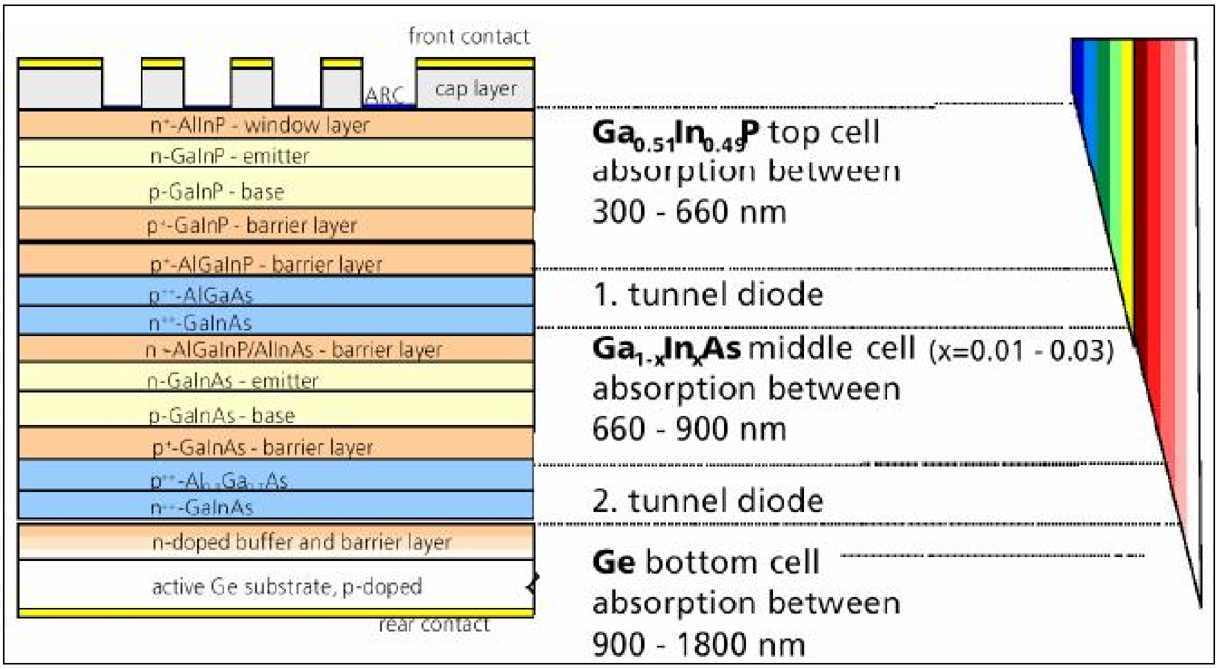

Figure 2-24: Scheme of the layers of a GaAs solar cell [RD 68].

A sketch of the performance attributes is depicted in Figure 2-25. It becomes apparent, that the higher costs of GaAs cells and the reduced availability of resources are outweighed by the operational benefits like radiation resistance and lifetime, improving overall mission reliability and performance.

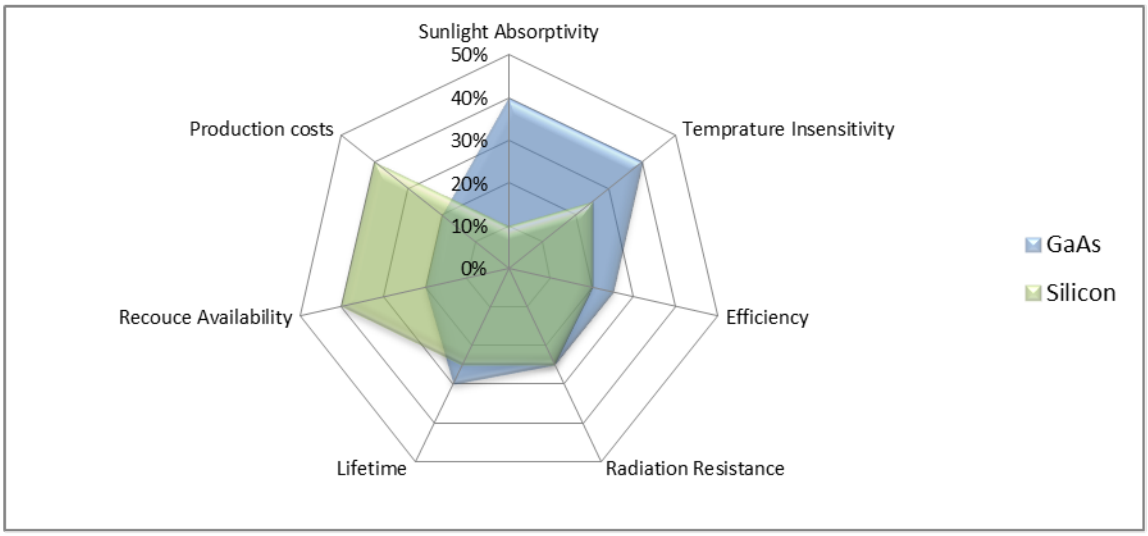

Figure 2-25: Performance Attributes for GaAs and Si Solar Cells.

History

Initial research on the photovoltaic effect led to its discovery in 1839 by Edmond Bequerel [RD 69][RD 63]and the first photovoltaic cell was constructed by Charles Fritts in 1883. Four years later, in 1887, Heinrich Hertz discovered the photoelectric effects, which received a theory in 1905 by Albert Einstein [RD 69].

In the following years, several materials were tested for solar cells, like selenium, cadmium or copper. In 1954 the Bell Laboratories produced the first silicon solar cell with an efficiency of 4-6%, which was improved to about 14% until 1960 [RD 69].

Usage of GaAs for solar cells began in the 1970s and their development reached a state in 1988, where they exceeded the efficiency of silicon based cells [RD 70], which in 1985 had reached an efficiency of 20% [RD 69].

From 1990 onwards, multi-junction GaAs cells became standard power systems for satellites [RD 66].

2.5.1.3 Ka-Band Communication

Usage of communication satellites is mandatory for the establishment of a globally connected world community. They can act as relays to transmit information or general signals from one place on Earth to the other, without direct line of sight between these locations.

Especially for rather constant demands in communication services, geostationary orbits (GEO) can provide reliable and easy to maintain communication links. Due to the fact that their position above ground is – not accounting orbit perturbations – constant, the antenna pointing is constant, i.e. satellite tracking is invariant with regard to time.

The suitability of geostationary orbits for communications purposes made created the necessity to regulate the usage of these orbits. Because of this, the celestial equator is divided into slots, reserved for the countries situated below the respective slot. Angular and actual distances to the neighbouring slots are regulated as well. This means that the number of GEO satellites is restricted and therefore the amount of transmittable data is as well.

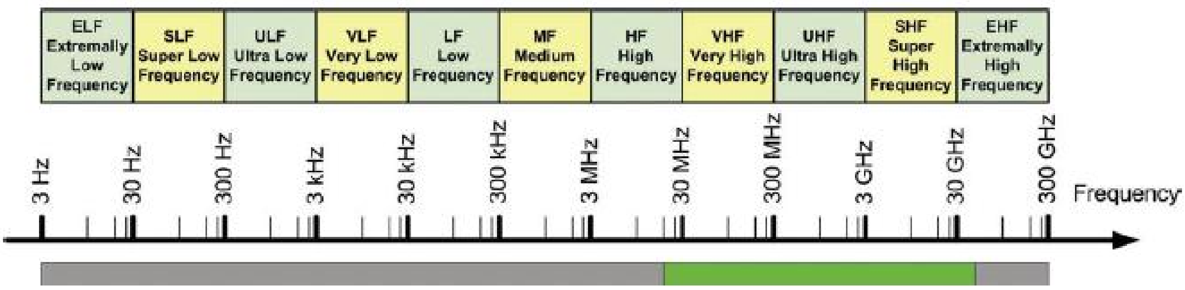

Figure 2-26: Radio frequencies [RD 71].

Figure 2-26: and Figure 2-27: show the classification of various frequencies for communication satellites, where Ka-band is the highest frequency band for satellite communication. The advantages of high frequencies, and thus especially of Ka-band communication, are higher rates of data transfer [RD 71] and smaller antennas [RD 72] (for the same gain, when compared with other frequency bands). At higher frequencies the interferences with other satellites are reduced and therefore positioning can be allowed closer than e.g. for X-band satellites [RD 71]. The large data rates also enable services like broadband internet, Voice over IP (VoIP) services and similar demanding operations to be executed by Ka-band satellites [RD 72].

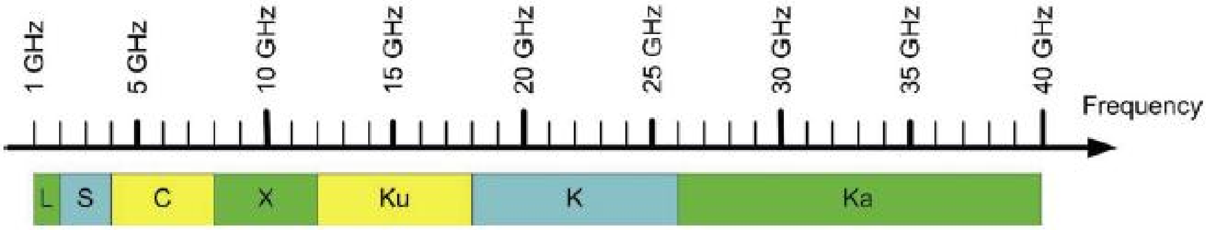

Figure 2-27: Satellite Communication Frequency Bands [RD 71].

Drawbacks for these kinds of satellites are on one hand that the signal attenuation by clouds and rain is more severe for these frequencies [RD 72] and on the other hand the power demand is also significantly increased [RD 71]. The latter problem can be remedied by more efficient solar cells and thus power generation of state-of-the-art GEO satellites, however. Regarding the former one, the frequency range that can be transmitted through the atmosphere is marked green in Figure 10, showing that the first half of the Ka-band is within this range, only the second half, i.e. frequencies above approximately 32 GHz are outside the range. However the frequency allocation for GEO satellite communication by ITU is restricted to 17.7 to 21.2 and 27.5 to 31 GHz [RD 73] and therefore the natural restriction to frequencies below 32 GHz is not relevant. Furthermore the downlink frequencies from 17.7 to 20.2 GHz are not shared by other satellite services e.g. in LEO and therefore the only constraint on the downlink communication is the coordination with terrestrial applications in the same frequency [RD 73].

Depending on the actual usage, typical geostationary satellites transmit in either C-band or K-band frequencies [RD 74].

The advantages and disadvantages of the Ka-band usage are sketched in Figure 2-28:, where it can be seen that apparently the increase in data rate outweighs the operational and organizational disadvantages of the power drain and signal attenuation.

History

In the year 1945 Arthur C. Clarke wrote the first article about the usage of geostationary satellites (back then it was though these were manned stations) for television broadcasting and of course in 1957 with Sputnik I the first radio transmitter had entered an orbit around Earth, even though it was not used as actual communication satellite [RD 75].

Only a couple of years later, in 1962, the first communication satellites, used for transatlantic television transmissions, Telstar 1 was launched, although not in a GEO orbit. This orbit type was first used for the Early Bird satellite in 1965 however, which became the first commercially used geostationary satellite [RD 75]. It used the L- and C-bands for communication during its operation [RD 76].

In the year 2006 the technology had evolved so far that Ka-band satellites like WildBlue-1 are commonly launched into a GEO with even more advanced techniques, like spot-beam transmissions [RD 77]. Satellites like the Spaceway constellation launched in the years 2005 to 2007 use Ka-band as well [RD 78].

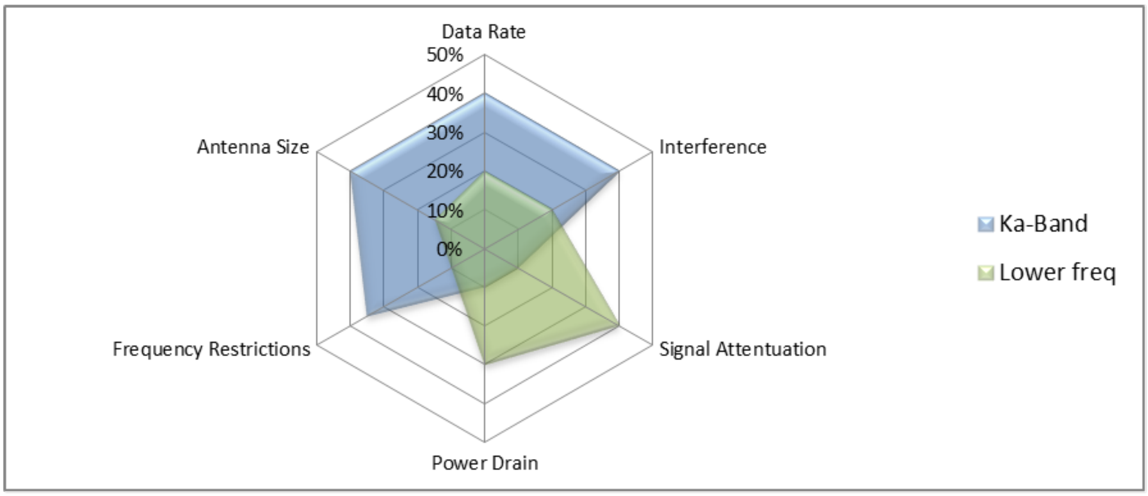

Figure 2-28: Performance attributes for Ka-band and lower frequency bands.

The adoption of Ka-band frequency for com satellites clearly shows how a shift of performance interests by the customer, caused by technological advancement (e.g. attenuation of signal is less important due to increase in transmission power enabled by more efficient power systems) allows other technologies to be adopted due to their improved performance in other fields, e.g. here data rate.

2.5.1.4 FPGA's and ASIC's

At the beginning of the age of consumer/mass-produced computers (early 1980s), all integrated circuits (IC) were designed with a specific task/application in mind. The development of these *Application-Specific Integrated Circuits* (ASIC) required a detailed blueprint of the microchip and resulted in high non-recurring expenses (NRE), as all components also had to be engineered for that one specific task. Once a microchip was green light for production, prototyping cost could be reimbursed, but not all designs reached this state.

The development of the so-called *Field Programmable Gate Array* (FPGA, first commercially sold by Xilinx Inc in 1985) improved on this concept: By providing a standardized set of components capable of multiple application areas, leaving the task specification up to the software side, development teams could try numerous designs with the same hardware. This resulted in a decrease in development time as well as cost.

The downside of FPGAs is, that their dimensions can be up to 35 times larger and their performance up to 4.6 times slower compared to ASICs. A more detailed comparison of the differences between the two is shown in the following tables:

FPGA & ASIC Design Advantages	
FPGA Design Advantages	**ASIC Design Advantages**
Faster time-to-market - no layout, masks or other manufacturing steps are needed	**Full custom capability** - for design since device is manufactured to design specs
No upfront NRE (non recurring expenses) - costs typically associated with an ASIC design	**Lower unit costs** - for very high volume designs
Simpler design cycle - due to software that handles much of the routing, placement, and timing	**Smaller form factor** - since device is manufactured to design specs
More predictable project cycle - due to elimination of potential re-spins, wafer capacities, etc.	**Higher raw internal clock speeds**
Field reprogramability - a new bitstream can be uploaded remotely	

Figure 2-29: Advantages of FPGA and ASIC [RD 79].

These advantages and disadvantages lead to the following radar chart:

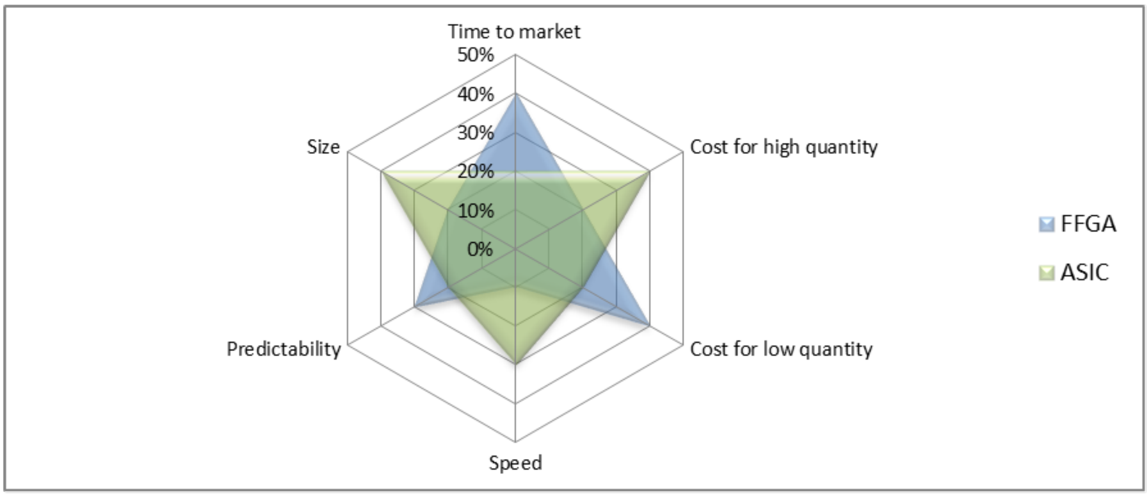

Figure 2-30: Radar chart comparison of FPGA and ASIC

To conclude, it shall be pointed out, that FPGAs did not supersede ASICs as both have found their specific fields of use. Nonetheless, the development of FPGAs is a good example of a disruptive technology as it re-defined how the manufacturing of ICs was approached.

2.5.1.5 Miniaturized Satellites

Since the first artificial satellite was launched which was Sputnik in 1957 [RD 80], satellites have become bulkier and heavier to cope with the increased demand on their performance. With this their costs have also increased, leading to; expensive to launch, expensive to design and long development time satellites. Miniaturized satellites are an opposite of this paradigm and focus on low costs to design, low cost for launch (through mass reduction, volume reduction and piggyback launches) and high flexibility. The low cost of designing is mostly gained through the use of Commercially available Off The Shelf (COTS) components, universal busses, low performance and low reliability requirements [RD 80].

These performance metrics open up a market for companies, universities and institutes, which are looking to have a cheap and flexible method to test technologies or perform experiments. Over time different types of miniaturized satellites have evolved, picosatellites (≤1 kg), nanosatellites (1-10 kg) and Cubesats (Standard size 10x10x10 cm 1 kg) [RD 80]. Picosats and nanosats are being launched primarily as secondary payloads (also named a piggyback launch).

Because of this, their cost is subsidized by that of the much larger satellite primary payload; launching them as primary payloads has been considered unprofitable. The cost of primary launches is far out of reach of picosat and nanosat developers. This secondary payload status places nanosat/picosat developers and operators at a disadvantage: they have little, if any, control over the primary payload's schedule and requirements—assuming that the launch provider is even willing to include secondary payloads. As summary miniaturized satellites have the following advantages versus conventional satellites:

Miniaturized satellites advantages:

- Low development costs
- Low launch costs
- Low hardware costs
- Low development time

Conventional satellites advantages:

- Higher performances possible
- Higher payload capability
- Longer lifetime

The difference in performance is illustrated in Figure 2-31.

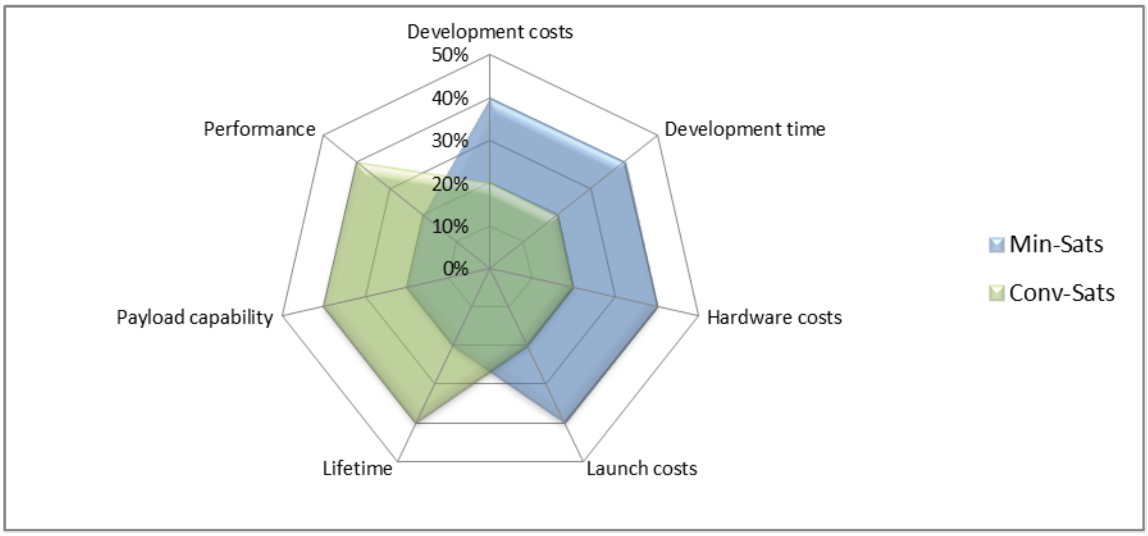

Figure 2-31: Performance parameters for miniaturized satellites.

History

The Explorer and Vanguard programs produced and launched what now may be considered the original nanosats, in the late 1950's. Vanguard 1, the second artificial US satellite successfully placed into orbit after Explorer 1 and the oldest artificial satellite still in orbit, would be considered the first picosat (1.4 kg) [RD 81]. Not long after, the Orbital Satellite Carrying Amateur Radio (OSCAR-1) in 1961 was the first nanosat to be carried and ejected as a secondary payload. Stanford University professor emeritus Robert Twiggs, along with Jordi Puig-Suari of California Polytechnic State University-San Luis Obispo, first developed the concept of CubeSats in 1999.

Although miniaturized satellites have not disrupted any existing technologies, they have opened up a new market that did not exist before, namely that as technology test platforms and responsive experiments by universities and institutes. However, since recently they are used for operational applications by using concepts like:

- MILTEC SMDC-One (Tactical communications data relay)
- QuakeSat (assessing ability to predict earthquakes) [RD 82].

In addition, concepts like swarm satellites or fragmented satellites have gained increased attention over the past few years. These concepts have the ability to allow miniaturized satellites to encroach on the market of conventional satellites in the future. The usage of miniaturized satellites has also increased over time as is evident by Figure 2-32.

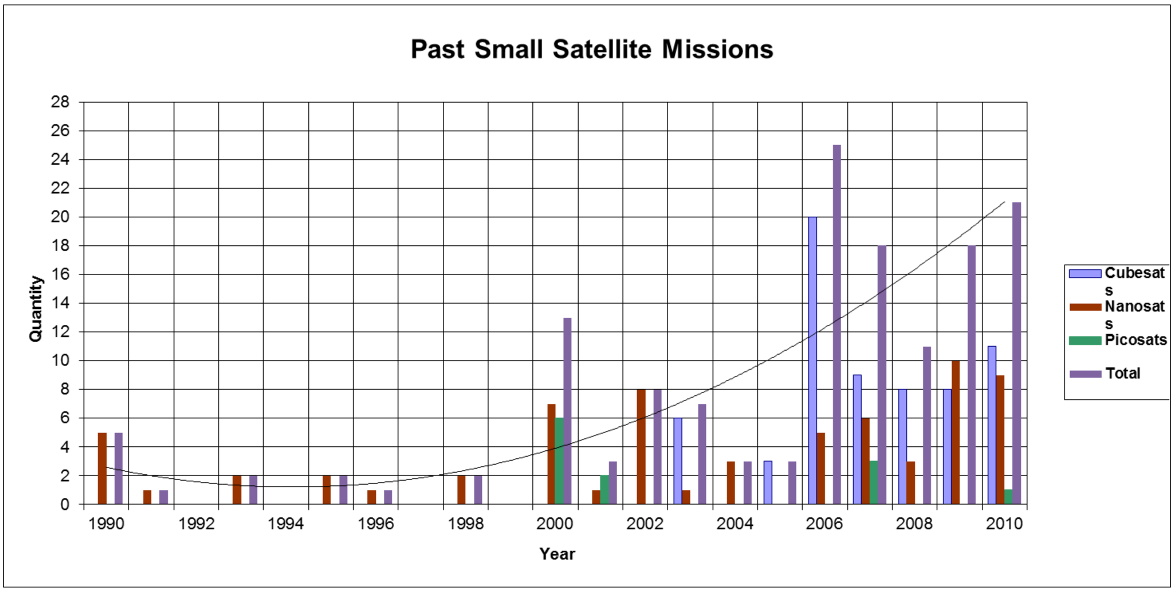

Figure 2-32: Performance parameters for miniaturized satellites.

2.5.1.6 Conclusion

After reviewing a range of technologies, several of these have been selected for further analysis as they are considered to be disruptive. This analysis consisted of a historical analysis as well as a comparison with the dominant technologies. In total five past DSTs were analyzed. When comparing the evolution of the past DSTs to the theory of DTs it can be clear that disruption does occur in the space sector although not precisely according to the theory defined by Christensen.

The major difference seems to be that with the disruption of technologies no major shifts were observable in companies marketing them. This is most likely caused by the long development time which allows incumbent companies to react to any changes in the market.

The past DSTs however do share the common characteristic that they have a different performance attribute mix compared to a dominant technology. They often start developing in a niche market before encroaching on the market of the dominant technology. In this case the DSTs are the same as DTs.

As a summary the following points differentiate DTs from DSTs (also from previous sections):

- **Development time**: The development of a space technology takes a long time; therefore the response time of incumbents to DSTs is high. They have the opportunity to either starting a development process of their own (if the development time permits it), or take over the company marketing the new technology.
- **Risk/Return on investment**: The long development time of a space technology means that the risk and return on investment is equally high, this is a barrier for new startup companies, as this makes it very hard to find investors.
- **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 [RD 83].
- **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 benefits reliability and decreases risk. A new space technology candidate has to be a significant improvement to the dominant technology to justify the increases in risk and decreases in reliability.
- **Incumbents versus new comers**: Space technologies do not need to be introduced by a new-comer and do not need to change the competitive layout of a market.
- **Market**: The space sector is a complex market which is highly influenced by governmental entities. Spread over the world, there are over 50 space agencies (e.g. NASA, ESA, JAXA, Roscosmos) more than 40 commercial operators and several institutional entities (e.g. NOAA, EUMETSAT, JME, EC) which are procuring satellites and satellite data. In addition, there are more than 15 satellite integrators. European companies sell to actors worldwide: more than 40% of activity is for commercial entities or entities outside of Europe. This makes the European space sector as a whole compete with the United States, Russia, Japan and more recently with India, China and Brazil. This section is explained more in the space sector infrastructure (Section 2.2).

Additionally DSTs can also be disruptive because they have an impact or they affect technologies in other domains. In some cases the way in which DSTs are combined with other technologies determines the disruptiveness of a technology. The committee on forecasting future DTs of the America National Research Council (2009) made categories to determine different kinds of DTs. If a technology has one or multiple aspects of these categories then its potential for disruptiveness will increase. These categories, adapted to the space sector, are:

- **Enablers**: A technology that makes one or more new technologies, processes or applications possible (e.g. integrated circuit => smaller Data Management Sub-System; Solar cell => rechargeable Space Craft).

- **Catalysts**: A technology that alters the rate of change of a technical development or alters the rate of improvement of one or more technologies (e.g. Cubesats/ swarm technologies; distributed systems, flash memory drive).
- **Morphers**: A technology that when combined with another technology creates a new technology (e.g. wireless technologies and microprocessors).
- **Spin-ins/spin outs**: A technology that crosses over from one market to another and disrupts the status quo in the new market (e.g. Nano tubes and medical scanners (Heide et al., 2009)).
- **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. (e.g., Solar Sail, Star Tracker)

2.5.2 Theory of Disruptive Space Technologies

Because of the reasons mentioned in the previous section, DTs, as described in business literature, are not the same for the space sector. Therefore, in the course of this work, an adjusted theory is developed for the space sector called: Disruptive Space Technologies. When analyzing the innovation literature and the theory of DTs, a resemblance can be found between Radical Innovations and DTs. Both are explorations of new technologies and replace dominant technologies, additionally they both offer a higher performance on the perceived performance mix. The key difference between these theories is that DSTs do this in an unexpected way, in other words by over performing on an alternate perceived performance mix. The key characteristics of DSTs can be summarized by the points below:

1 DSTs are product innovations according to the 4P paradigm (Product, Process, Paradigm and Position innovation) of Francis [RD 6], because a technology is always a product innovation. This research will only be applicable to forecast space technologies. (As an example: Commercial space is a paradigm innovation, while a commercial spacecraft is a product innovation.)

2 DSTs are exploitations of new technologies. This means that they represent a significant improvement in technology along a discontinued perceived performance mix of a part of the market. Therefore the technology replacement of DSTs can be characterized as an unexpected event in the space sector.

3 A concept with a DST potential is in the fluid phase or concept phase of a technology as depicted in the Abernathy & Utterback [RD 13] model in Figure 2-3. This means that their greatest competitor is the dominant space technology. Usually the technology has not been tested yet in the operating environment. The disruption of the dominant technology occurs in the transitional phase. In the specific phase the technology gains extensive flight heritage and reaches the end of it potential gain in performance.

4 A technology can still be disruptive if it does not disrupt incumbents by new entrants. 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. Disruption is however caused by market factors (perceived performance mix) other than technological factors (performance).

5 DSTs usually focus on simpler, cheaper, more flexible and/or more responsive compared to the incumbent technology.

The insights mentioned above lead to the following definition of DSTs:

A disruptive space technology radically changes the status quo of the space sector by fulfilling user's technology requirements better than a dominant technology

2.6 Summary

This chapter shows a literature study on innovation in general, followed by a literature review of DTs. After this, the space sector infrastructure is analyzed with addition to different key-players. This lead to an analysis of the space sector infrastructure with respect to technology development and it was found that technology development is divided along mission focused pull factors and basic research push factors. These let to the following conclusions:

- Development paths are usually long and time consuming and not always continuous as technology development in later stages mostly depends on mission application, which is not guaranteed.
- Technology development can be divided into two kinds: push and pull, where the former means it is developed due to the expectation of an up-coming need and the latter means the development is driven by technological requirements of an actual mission.
- There are several technology programs, divided over different levels throughout the space sector, supporting push development through basic technology research.
- Technology pull constitutes the largest part of technology development in the space sector. This kind of technology development does however not lead to major improvements of the space sector in general because of a relative small degree of freedom in taking risks. After this, a series of past DSTs are analyzed and resulted in several conclusions that differentiated DSTs from DTs. Major conclusions were:
- Disruption in space does not include the disruption of companies
- Disruption in space does include the over performance along different performance dimensions.

3 Spacecraft System Categorization

In order to identify and describe, how a potential DST can improve or alter a spacecraft design, the following chapter serves as system categorization baseline. This baseline is to be used in further work packages, to pinpoint affected areas of a DST.

In addition, a functional analysis of spacecraft subsystems is conducted to highlight subsystem dependencies. The dependencies in the following provide a basis for the present study's search scope for Disruptive Space Technologies.

3.1 Category Definition of Spacecraft and Surrounding Areas

In order to manage the vast diversity of space activities, a proper classification is needed. This classification offers an overview of the research field and provides a raster, which is beneficial for the subsequent analysis.

Activities in the space industry can be summed up to (SIA 2009):

- Satellite manufacturing
- Satellite services
- Ground Equipment manufacturing
- Launch industry

Satellite services are hereby understood as commercial services (e.g. broadcasting, communication, navigation). In addition to these, scientific missions like deep space observation and exploration, as well as military purposes have to be included, which could be labeled as institutional services.

These activities e.g. differ in their requirements, mission goals and publicity. For example the development and manufacturing of scientific missions, especially exploration type endeavors, like *Dawn* or *Rosetta*, is usually very individual and unique. On the other hand the manufacturing of commercial satellites is often done in small series' or based on one family of bus models, e.g. like *Galileo*, Europe's satellite navigation network.

Other areas, like space tourism or human spaceflight in general, differ in their requirements, e.g. by more strict needs for reliability in order to reduce the risk of lives lost during a mission. Also for space tourism the payload is not scientific instruments, but accommodations for passengers. The performance is measured by entertainment not scientific value.

For purposes of this scientific investigation, in form of a data analysis, conducted later on, it was decided to resort to an already existing classification with a greater level of detail. The utilization of ESA's Technology Tree [RD 84] allows a precise description of the scope of the investigation. It was therefore used for the generation of the needed segmentation of space segments, described in the next section. The following paragraphs will describe this technology tree on various levels.

The three typical space system segments are given in Figure 3-1. In this nomenclature, the space segment contains the spacecraft with its payload, the transfer segment provides its transport into orbit via a launch vehicle and the ground segment resembles the equipment used for operating the spacecraft.

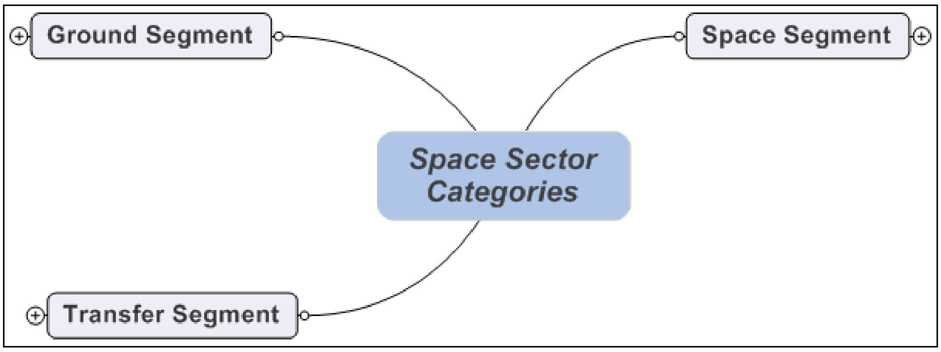

Figure 3-1: Space sector main categories.

Although this classification provides a suitable example for an overview of different space systems, it has certain limitations like the lack of sufficient level of detail; also it does not consider all space system segments.

Issues directly linked to the space segment are listed in Figure 3-2 and Figure 3-3. Examples are spacecraft subsystems like *spacecraft electrical power*, *on-board data system*, *propulsion* and *mechanisms & tribology*. Additionally, *EEE* (Electric, Electromechanical & Electronic) *components and quality* for on-board electric/electronic systems; *materials and processes* like novel materials not yet used in space but presenting potential interest and more refer directly to the spacecraft and its payload.

The *RF payload and systems* and the *automation, telepresence and robotics* are also directly connected to the spacecraft and its payload. The former covers all technologies and techniques related to satellite systems and networks, spacecraft payloads, and ground equipment, for telecommunication, TT&C, navigation, Earth observation and space science, operating up to microwave or millimeter-wave frequencies. The latter covers *automation, telepresence and robotics*, which include space robot systems, and space laboratory automation and payload control systems in manned and unmanned missions [RD 84].

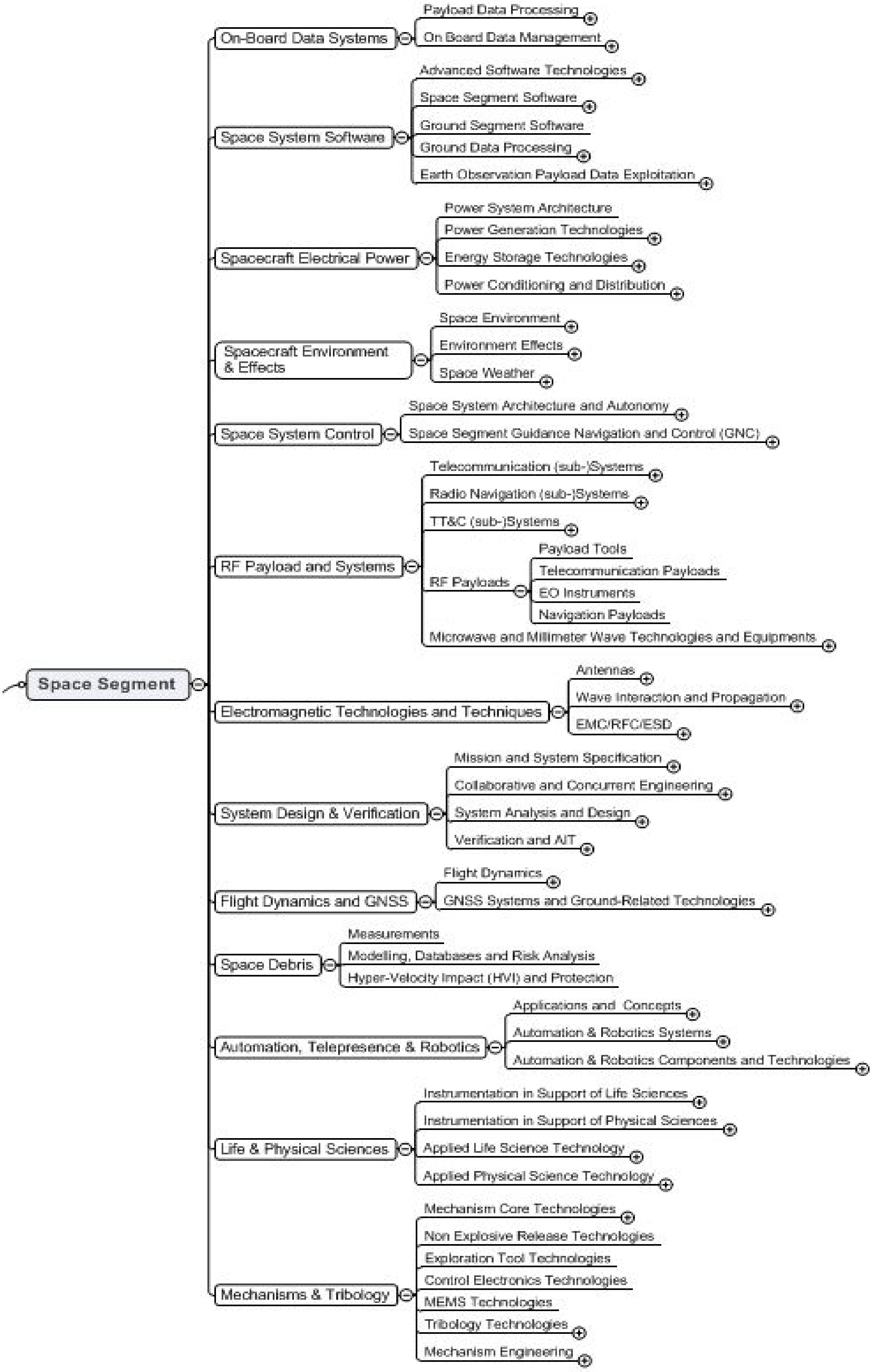

Figure 3-2: Space segment categories (part 1).

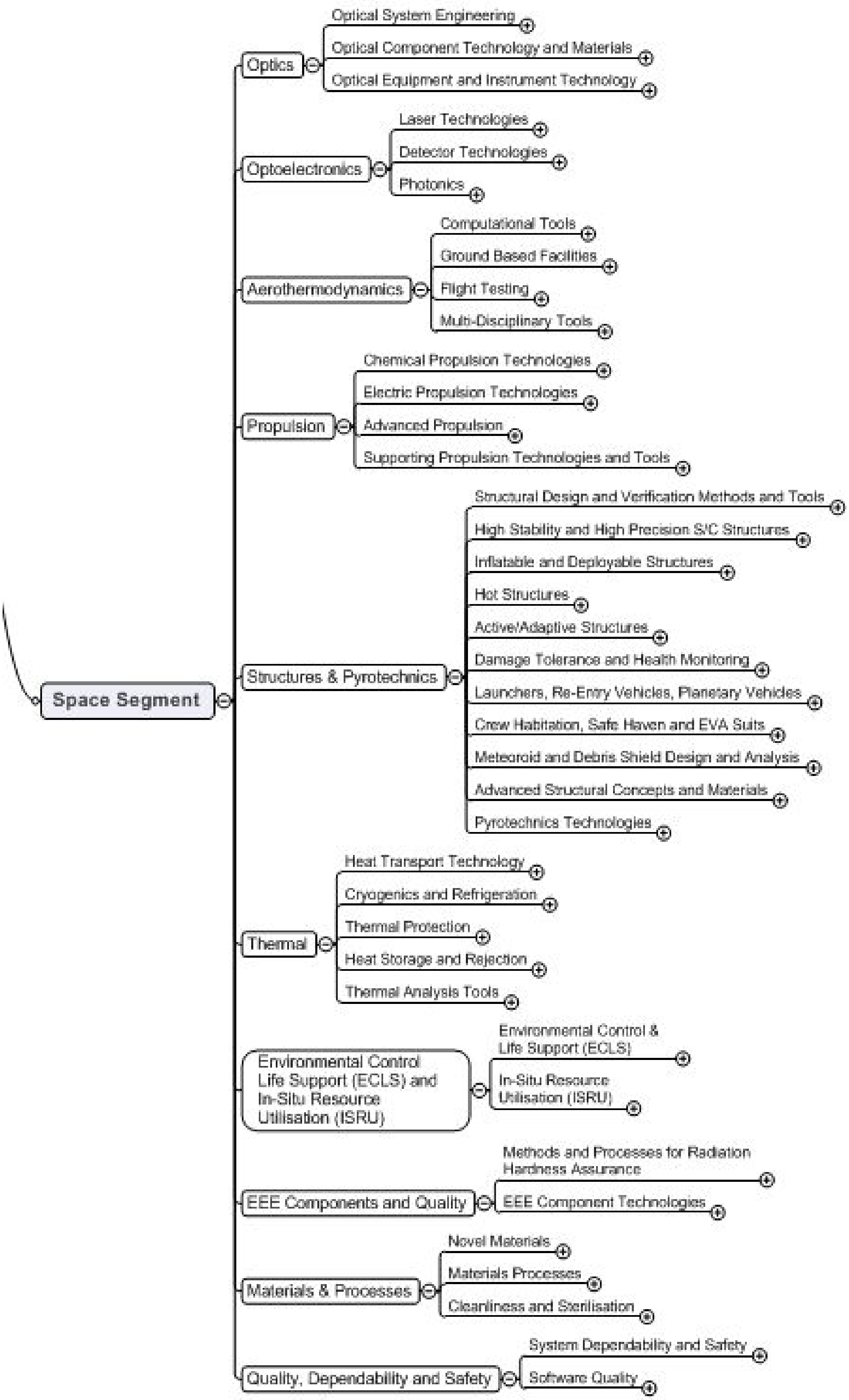

Figure 3-3: Space segment categories (part 2).

The transfer segment with the *launch campaign* and the *launch vehicle* contains a set of activities which prepare a launch vehicle and its payload (spacecraft) for lift-off. Activities during the launch campaign include *spacecraft assembly & functional tests*, *launch vehicle assembly*, *payload integration*, *fuelling of the launch vehicle*, and *launch pad preparation*, the *launch range* and *tracking stations* [RD 85].

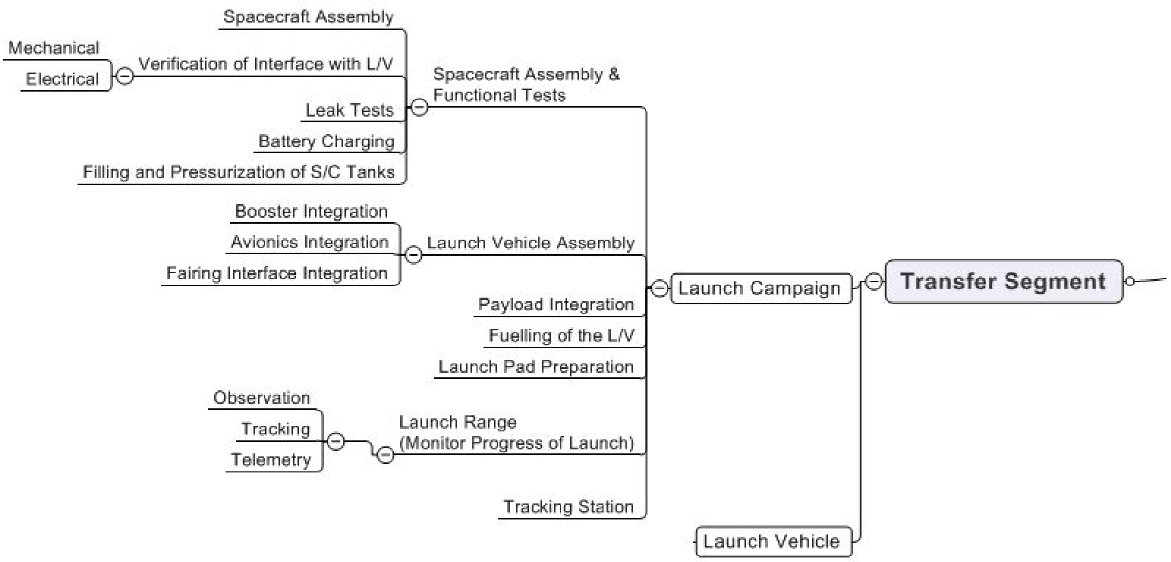

Figure 3-4: Transfer segment categories.

The ground segment covers the elements and know-how required for the engineering of the facilities that connect the space segment (spacecraft) with the control centers, e.g. *mission operation and ground data systems* and *ground station systems and networks* attributes.

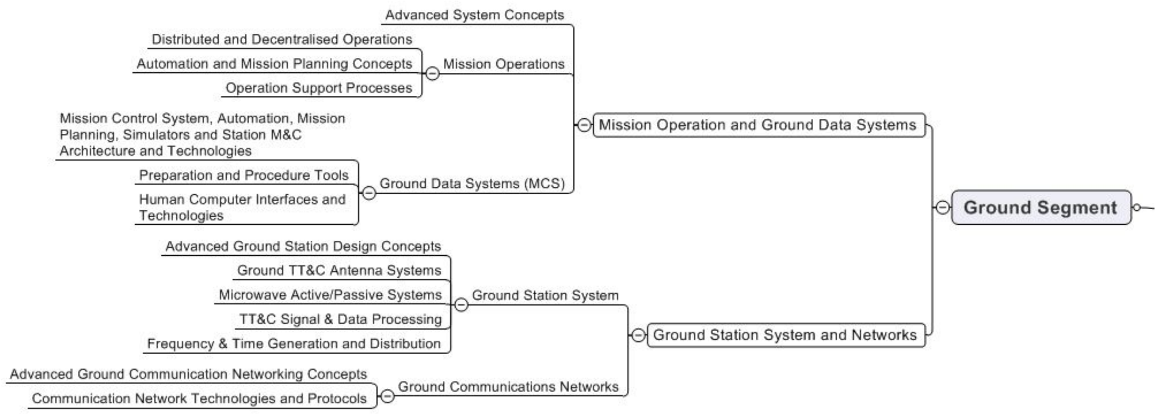

Figure 3-5: Ground segment categories.

Each potential DST, which can be transferred to the space sector does not necessarily replace or is assigned to a dominant space technology or system. The potential DST possibly only covers one or some functions of the dominant technology, not necessarily all of them. The breakdown on space system functions is helping to identify the potential of a technology being disruptive in the field of space.

Additionally the system's breakdown to their functions allows identifying dependencies between functions and so between systems. The visualization of the effects and consequences of replacing a dominant technology by a potential DST can be improved with this approach/procedure.

3.2 Subsystem Function Analysis and Definition

In the following functional analysis only the space segment is considered. With regard to Disruptive Technologies, both transfer and ground segment usually involve technologies and equipment with high initial development cycles after which long lasting phases of continued use and incremental innovations follow. In contrast, spacecraft systems are built with higher frequency, thereby presenting a platform with more sensitivity to DSTs and a more visible manifestation of them.

To be able to evaluate how a DST could improve an existing spacecraft, its effects on system and subsystem level need to be highlighted. To allow this for future detected DST candidates, a clear definition of all subsystems, as well as their common components and functions shall be elaborated in this section.

The Systems Modeling Language (SysML) was chosen to depict these relationships. SysML is a methodology to model functional dependencies (e.g. mass of batteries as a function of solar array area) and can also be used to visualize system architectures. It is based on the Unified Modeling Language (UML) a language primarily used for software-centric development, adapted to the specifics of systems engineering.

Subsystems are implemented as "classes" and are symbolized through a rectangle. Each rectangle in turn consists of three elements, separated through horizontal lines:

1. the class name at the top (followed by '::'),
2. class attributes in the middle (equivalent to spacecraft components)
3. and operations on the bottom (equivalent to subsystem functions).

Even though there can be up to 23 domains related to the spacecraft design (represented e.g. through the experts presented in a Concurrent Engineering study [RD 86]), the present study will focus on the seven main subsystems:

- *Attitude and Orbit Control*,
- *Data Handling*,
- *Electrical Power Supply*,
- *Propulsion*,
- *Structure and Mechanisms*,
- *Telemetry and Telecommand*,
- *Thermal Control*.

The remaining 16 domains are either regarded subsets of the main seven subsystems (e.g. *Pyrotechnics* as part of *Structure and Mechanisms* or *Environment* as part of *Thermal Control*) or do not as such have a relation to technologies (for example *Mission Analysis*, *Configuration* or *Cost*).

3.2.1 Listing of Spacecraft Subsystems

With respect to the definition of search scope, this sub-chapter depicts relationships respectively dependencies between subsystems. Besides changing the functionalities of subsystems (e.g. a decentralized data handling) and replacing or improving specific components, DSTs could also alter how subsystems interact with or depend on each other. This sub-chapter establishes a basis to describe these relationships.

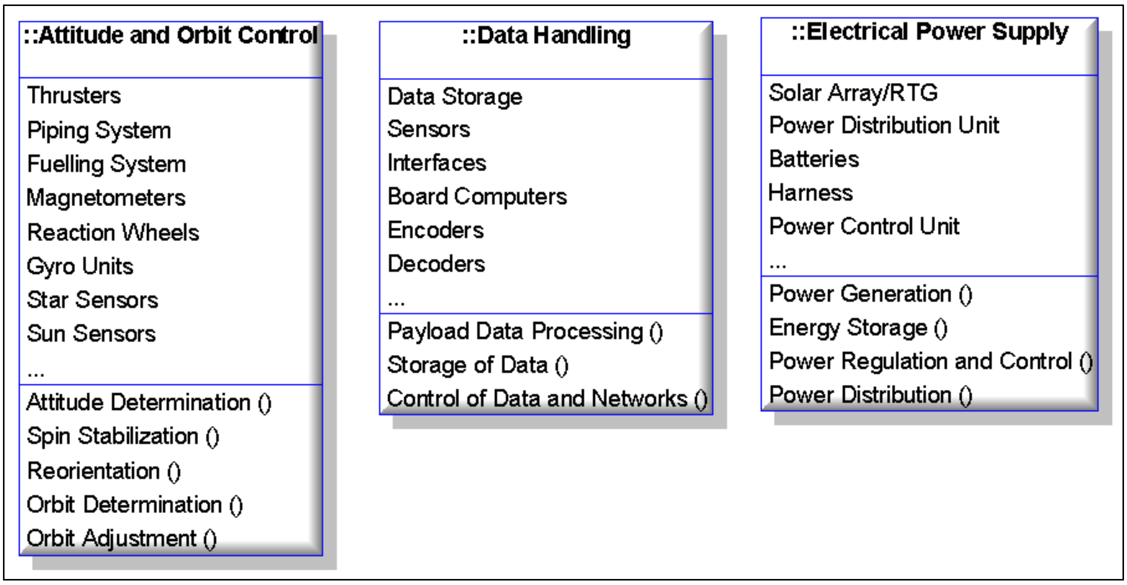

Figure 3-6: SysML representation of Data Handling, the Attitude and Orbit Control and the Electrical Power Supply subsystem.

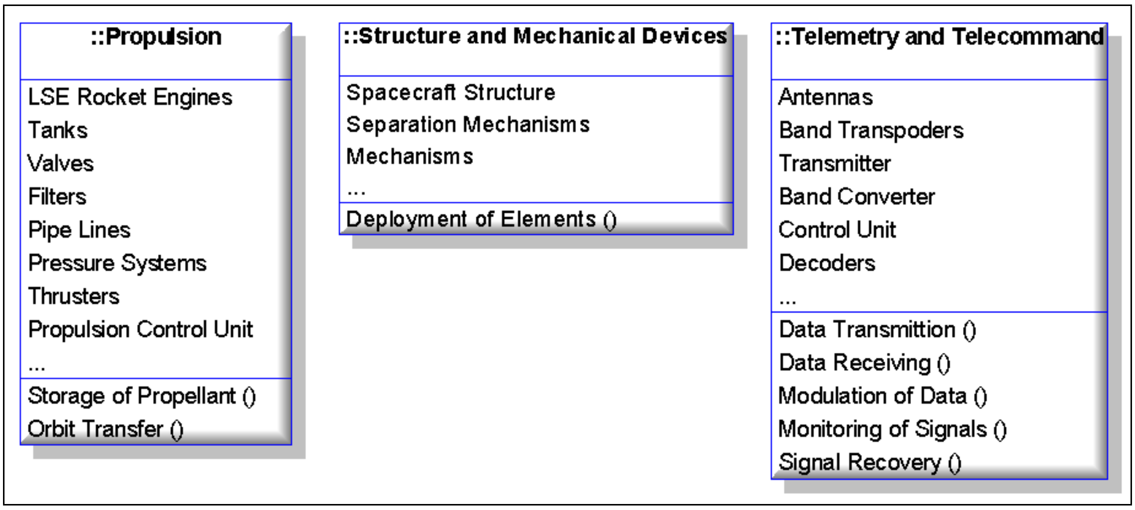

Figure 3-7: SysML representation of the Propulsion, the Structure and Mechanical Devices and the Telemetry and Telecommand subsystem.

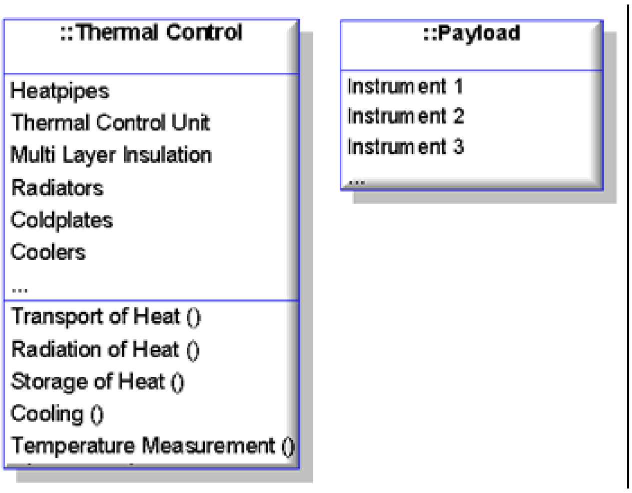

Figure 3-8: SysML representation of the remaining Thermal Control subsystem as well as the payload.

3.2.2 Analysis of Causal Dependencies between Subsystems

While the subsystems were already described before, the dependencies and interactions are expressed through different arrows within the systems map shown in Figure 3-9. Arrows can either be uni- or bidirectional and represent dependencies (e.g. electrical or thermal requirements) and/or exchange of data/information (for example the values measured by a sensor). For example the *Attitude and Orbit Control* subsystem transfers attitude data from a star sensor to the *Data Handling* subsystem, which in turn might relay this information to the *Telemetry and Telecommand* subsystem for transfer to a ground station.

On the other hand the same line of information processing can be followed inversely. A ground station submits a command to a spacecraft via the *Telemetry and Telecommand* subsystem, from where it is transferred to the onboard *Data Handling* subsystem. This interprets the command for and relays it to the *Attitude and Orbit Control* subsystem, which then executes the command by e.g. firing a thruster.

As previously mentioned, the *Payload* is depicted as central element of the SysML model. The analysis identified three types of characteristics regarding the role of a subsystem:

- the global task,
- the triple-dependency
- and the single dependency

The first one is the ‘global task’: Both the *Structure and Mechanisms* and the *Electrical Power Supply* subsystems are related to all other subsystems by directly connecting all components of the spacecraft respectively by supplying each element with power. This is expressed through a circular arrow (for *Structure* in blue, for *Power* in orange) to connect all related subsystems as well as through simple pointers to represent the payload dependency, i.e. supplying the payload with electrical power and with structural integrity.

The second type can be described as 'triple-dependency' of subsystems (depicted trough the green, bi-directional arrows). One such relation would be the previous example involving the *Data Handling* subsystem, also referred to as DHS.

As laid out before, *DHS* is the main element to communicate between *Telemetry and Telecommand* and *Attitude and Orbit Control* subsystem (AOCS, not equal to Guidance, Navigation and Control or GNC, but commonly used in an exchangeable manner), implementing attitude change instructions received from Earth or resulting from payload demands (as an assignment through the former triple-dependency).

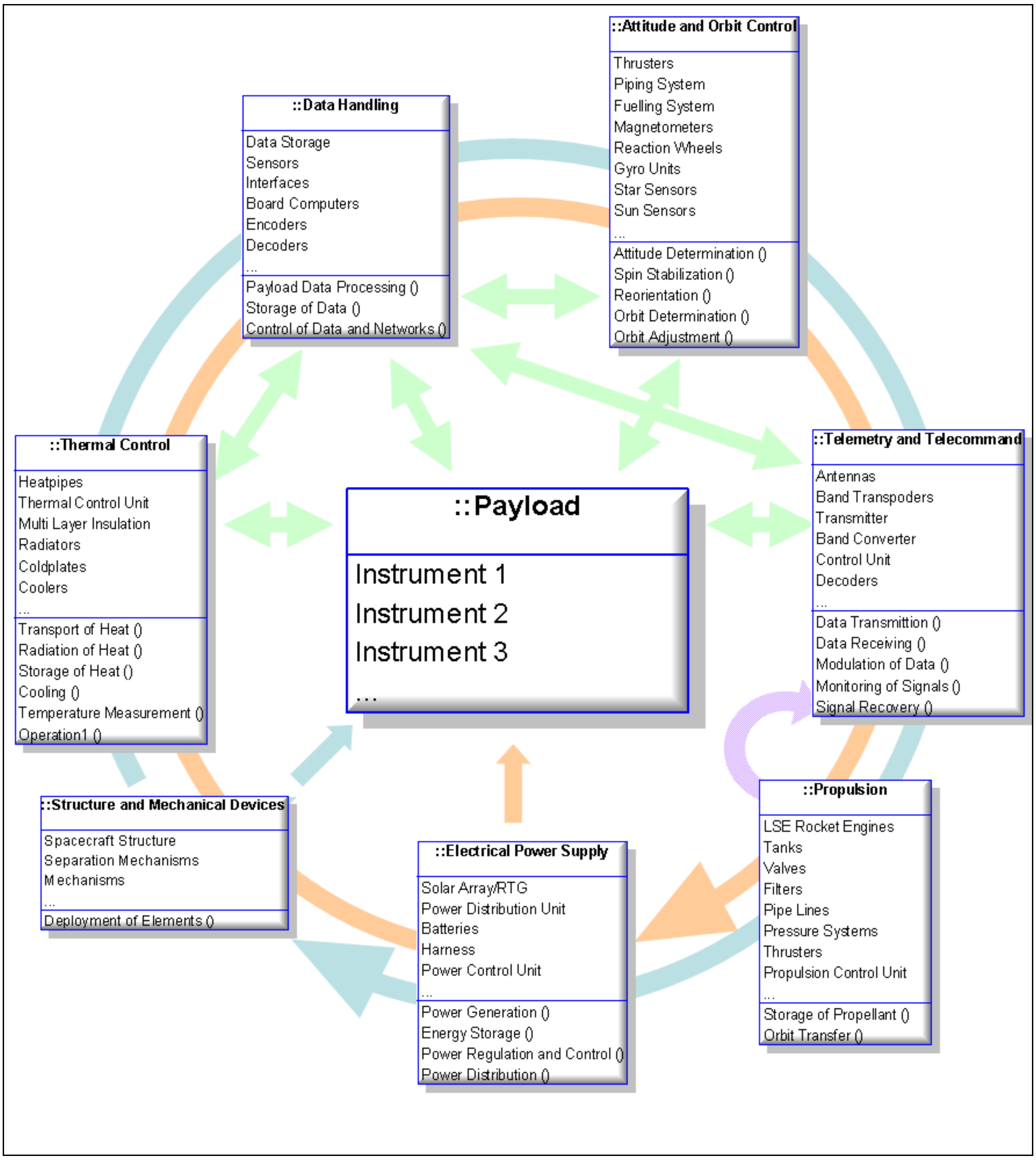

Figure 3-9: The general spacecraft system map (green, bidirectional arrows: triple-dependency; orange/blue: global power supply/structural task; purple: single dependency).

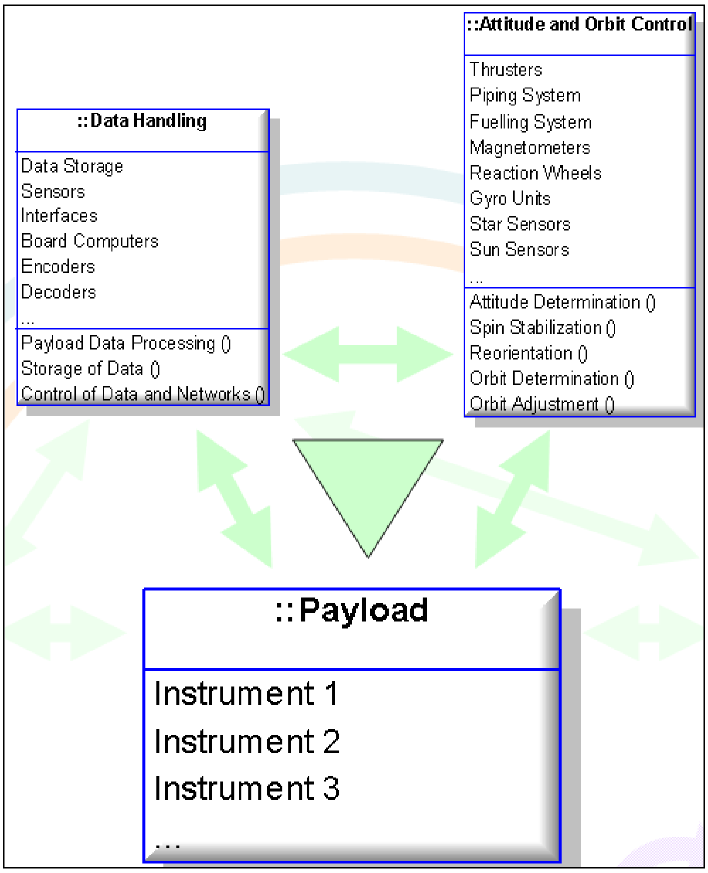

Figure 3-10: Triple-dependency involving *Data Handling*, *Attitude and Orbit Control* and the *Payload.*

To emphasize the involvement of three subsystems, Figure 3-10 includes a supplemental triangle. It can also been draw between the other subsystems connected through the green arrows (depicted in Figure 3-11 and Figure 3-12).

As a second triple-dependency, *DHS* is the major element between the *Payload* and the *Telemetry and Telecommand* subsystem, interpreting and translating data between the latter two Figure 3-11:

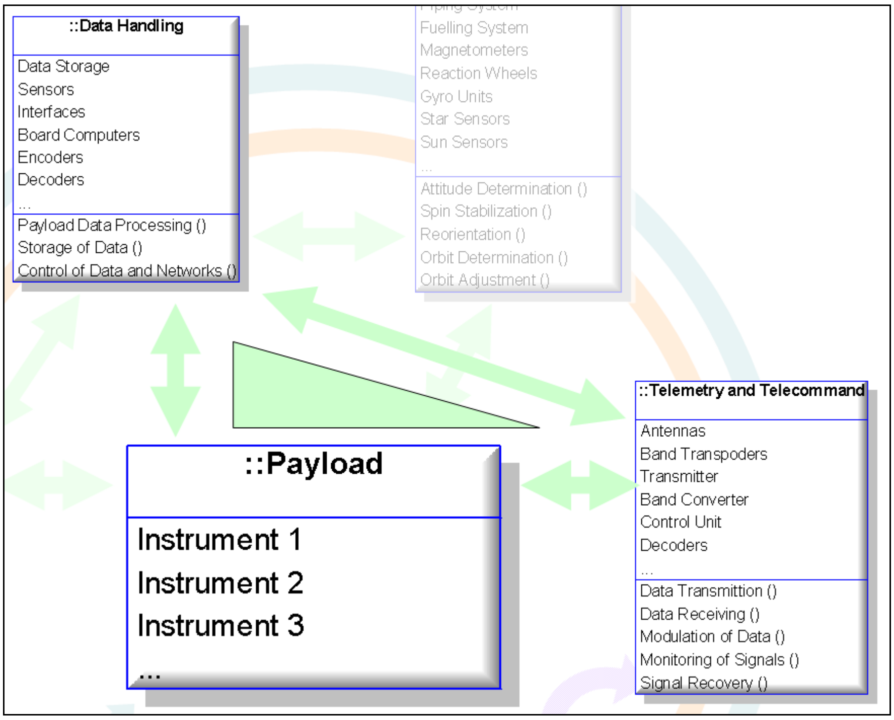

Figure 3-11: Triple-dependency involving *Data Handling*, *Telemetry and Telecommand* and the *Payload*.

The third triple also involves the *DHS*. Again as major element, *DHS* delegates temperature information between the *Payload* and the *Thermal Control* subsystem Figure 3-12:

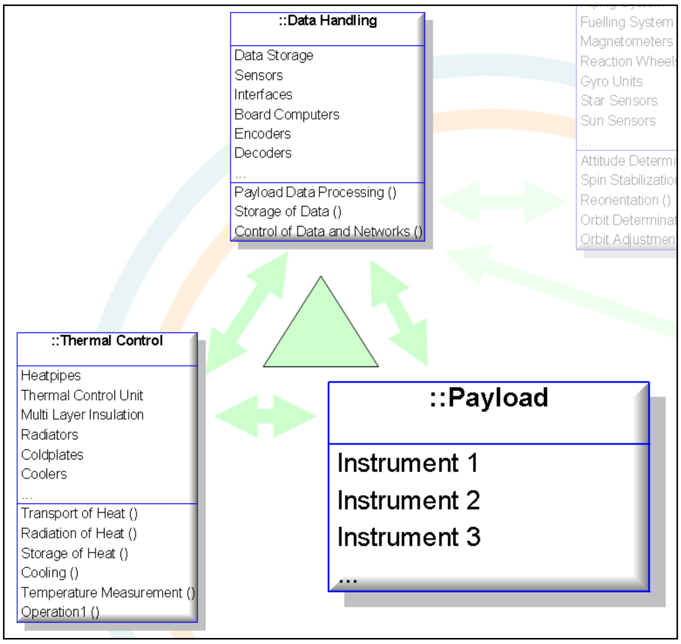

Figure 3-12: Triple-dependency involving *Data Handling*, *Thermal Control* and the *Payload*

The reliance on a single element (DHS), through which multiple functional dependencies are channeled is described as bottleneck. The triple depicted in Figure 3-12 can be seen as an example currently already involved in major changes as *Thermal Control* systems are equipped with separate data handling systems, thus becoming independent of the classic *DHS*.

As a subsystem only depending on one other subsystem, referred to as 'single dependency', the *Propulsion* subsystem is an example of a rather independent system, usually involved in only one task at the time. It is illustrated through the purple arrow in Figure 3-13.

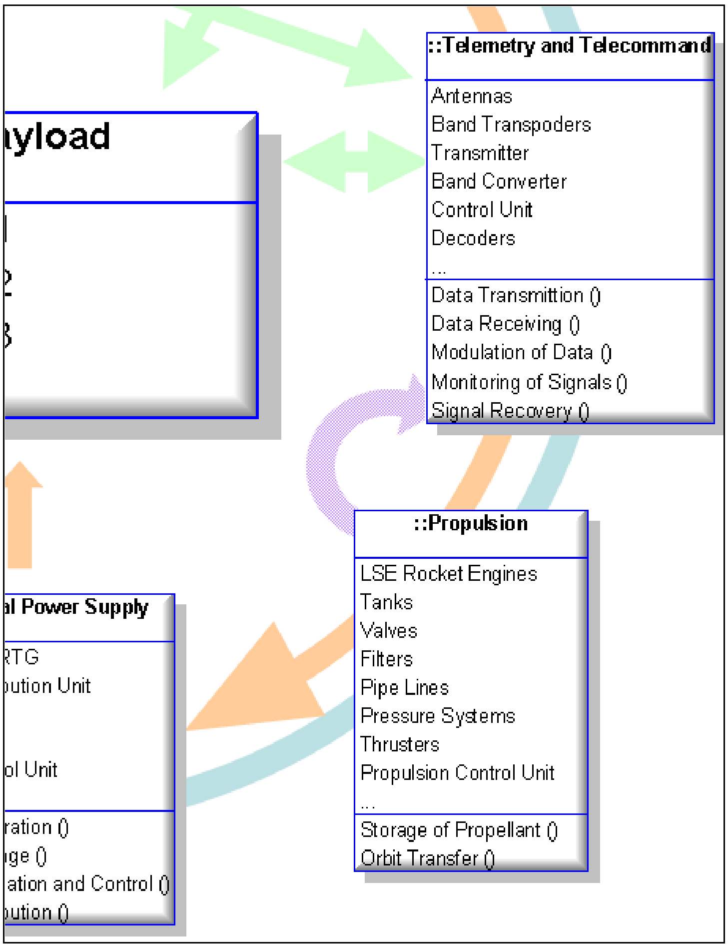

Figure 3-13: The single dependency between the *Telemetry and Telecommand* and the *Propulsion* subsystem (purple arrow).

Propulsion is herein referred to in the classical sense, being in charge of orbit insertion and sending the spacecraft into its graveyard orbit or its corresponding final destination at the end of the mission. Both are communicated through the *Telemetry and Telecommand* subsystem.

The dependencies covered in the system map do not include all dependencies to be found between spacecraft subsystems. The three types were identified with the predefinition of the search scope (chapter 3.3) and provide a decision baseline in the following, to clarify why the chosen direction was selected.

3.3 Predefinition of Search Scope

Since the space sector has a vast number of technology domains and analyzing them all for DSTs would require a considerable amount of time, the decision has been made to limit the search scope on a few technology domains. Based on the system map from Figure 3-9 four technology domains are selected on their impact on the space sector and spacecraft.

As visualized in Figure 3-9 the Electrical Power System (EPS) is essential for the operation of any space system. Therefore one major branch of investigating potential DSTs will be *Spacecraft Electrical Power* field as specified in the Tech Tree [RD 84] in the analysis subsequent to this work package.

Another major constituent of any spacecraft is the Structure & Mechanisms domain (cf. Figure 3-9). Elements like harness, mechanisms, as well as framework occur in any space system and therefore advances in these fields, either architectural or material, can significantly affect the space sector. Materials can primarily influence system mass if strength or other material properties allow lightweight frameworks. According to Stellmann [RD 45] typical ranges for the subsystem mass ratio of the structure subsystem for exploration missions are between 20 to 40%, i.e. impact on this subsystem's mass can be considerate regarding the total spacecraft as well. Consequentially the *Materials & Processes* section of the Tech Tree [RD 84] will be further investigated in the ongoing work.

A third major part of any space mission is the *Propulsion* field (named identically in Figure 3-9 and the ESA Tech Tree). This spacecraft subsystem is required for launch, orbit-insertion and perturbation correction. While only large spacecraft, especially GEO-satellites in terms of apogee-motors, carry own propulsion systems, orbit insertion and launch are mandatory for all of them. Especially high-cost exploration missions are also mainly shaped by propulsion capabilities, regarding Delta-V, efficiency, power drain of the propulsion system, etc. Due to propulsion being a necessary condition for any space mission, it is therefore also included in the search scope.

Following the diagram in Figure 3-12 the Data Handling subsystem inherits a critical position with regards to inter subsystem communication or data exchange. To avoid this single-point dependency, current spacecraft subsystems already employ smaller, decentralized processing components. In case of the already mentioned Thermal subsystem, this component is known as the TCU or Thermal Control Unit. The decentralization guarantees an autonomous functionality in the event of a failing, related subsystem (here DHS) and was possible through progress in the miniaturization of technology. The combination of miniaturization and decentralization is seen as one trend, the search scope for this study focuses on in subsequent work packages. Small, self-sufficient components or cells, not only with respect to data handling task, have the potential to change the current approach of redundancy, one of the most critical elements of spacecraft design. Therefore *On-Board Data Systems* [RD 84] will be investigated further in the coming analysis.

Because DSTs often result from cross-functional fields, a part of the search scope is also to analyze the adjacent fields of the space sector for potential spin-ins.

- Photonics (usage of light/ optical technology for various applications like communication and measuring)
- Advanced Materials (lightweight materials, fibers)
- Micro- and Nanoelectronics
- Biotechnology
- Information and Communication Technologies
- Robotics

Under consideration of the above stipulations the Broadcast Scan (TN03), is conducted.