Measuring Space Systems Flexibility:
A Comprehensive Six-element Framework

by
Roshanak Nilchiani

M.S. Engineering Mechanics, University of Nebraska-Lincoln, 2002
B.S. Mechanical Engineering, Sharif University of Technology, 1998

SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN
AEROSPACE SYSTEMS
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2005

Author……………………………………………………………………….…………………….
Space Systems Laboratory, Department of Aeronautics and Astronautics

Certified by……………………………………………………………………………….
Daniel E. Hastings, Thesis Committee Chair
Director, Engineering Systems Division
Professor of Engineering Systems and Aeronautics and Astronautics

Certified by…………………………………….……………………………….………………
Joseph M. Sussman, Thesis Supervisor
Professor of Civil and Environmental Engineering and Engineering Systems

Certified by……………………………………………………….……………………………
David W. Miller, Thesis Supervisor
Associate Professor of Aeronautics and Astronautics

Accepted by……………………………………………..………………………………..
Jaime Peraire,
Professor of Aeronautics and Astronautics
Chair, Committee on Graduate Students

Measuring Space Systems Flexibility: A Comprehensive Six-element Framework

by
Roshanak Nilchiani

Submitted To the Department of Aeronautics and Astronautics In Partial Fulfillment of The Requirements For The Degree Of
Doctor of Philosophy In Aerospace Systems
At the **Massachusetts Institute Of Technology**

Abstract

Space systems are extremely delicate and costly engineering artifacts that take a long time to design, manufacture, and launch into space and after they are launched, there is limited access to them. Millions of dollars of space systems assets lost annually, when the space system has failed to meet new market conditions, cannot adapt to new applications, its technology becomes obsolete or when it cannot cope with changes in the environment it operates in. Some senior leaders have called for more flexible space systems. The existence of flexibility can help it adapt itself to the change at hand, or even take advantage of new possibilities while in space.

Yet in the absence of a practical way to measure its value, most decision-makers overlook its implementation in their space systems. Although the literature is not lacking in number of flexibility measures, there is a void in articulating a unified and comprehensive framework for measuring the multiple aspects of flexibility in space systems.

This research is an effort to provide such a framework based on the common fundamental elements that define the nature of flexibility in space systems and other engineering systems. Through the extraction of common elements of flexibility from 25 major papers in the field of space systems flexibility, more than 60 papers in the field of manufacturing flexibility and 43 papers in the field of systems engineering, this dissertation identified uncertainty, time window of change, system boundary, response to change, the system aspect to which flexibility is applied, and access to the system as the six key elements that affect the value flexibility. Based on the six elements, the 6E Flexibility Framework was proposed as a twelve-step framework that can guide decision-makers in assessing the value of flexibility in their system.

The framework was then applied to four case studies dealing with a variety of space systems (commercial, military and scientific) with monetary and non-monetary value delivery, at different scales (satellite level, fleet level), different time windows of change and with regards to different aspects of flexibility (life extension, instrument upgrade, capacity expansion) facing different kinds of uncertainty (technological change and market uncertainty). The case studies demonstrated the ability of such a framework to provide decision-makers with the information necessary to integrate flexibility in their design and operational decisions and showed that the 6E Flexibility framework could be applied across different aspects of a system easily, capturing the impact of flexibility on design of and decision-making for space systems.

Acknowledgement

I also dedicate this work to the memory of my uncle Morteza Mohebbi-Taban, who provided me with my first scientific books at the age of six, who brought me my first telescope and opened to me the awe for a universe far beyond the confines of our earth. I owe my passion for knowledge and scientific exploration to him. The passion he filled me with will continue to take me on a journey that may never end as long as I am alive.

My love for Ali, my soul mate, has been the source of much of the energy for my explorations in the past 10 years. During all the difficult times of the past few years, he has been on my side, giving me courage to face the professional and personal challenges I have faced while at MIT. Without his support, this dissertation would not have been possible.

My family has been a major source of support and love, and I would not be here if it were not for them. My sincere love and thanks to my mom Tahereh Mohebbi-Taban, my father Masoud Nilchiani and my siblings Azadeh and Mani. My affection for my uncle Reza Mohebbi-Taban, my aunt Azarakhsh Etemadzadeh and their encouragement of my scientific quest deserves a special thanks. My grandmother, Zahra Ghorbani, whose wisdom has given me the gift of life deserves my deepest gratitude. The unwavering support of my in-laws, Jalil and Enci Mostashari allowed me and Ali to take this opportunity to explore the world beyond the borders of our birthplace. They are also high on the thank you list.

I would like to express my gratitude to all those who provided me with guidance in completing this dissertation. I would like to thank Prof. Daniel E. Hastings for his thorough guidance and supervision of this work and for providing me with an opportunity to work on such an exciting and challenging topic. I would also like to thank my doctoral committee Prof. Joseph M. Sussman and Prof. David Miller for their support and guidance and their excellent feedback throughout the process. Many thanks to Prof. Annalisa Weigel and Prof. Oliver De Weck for accepting to be my thesis readers, and for providing valuable input on this research. I would like to acknowledge the support of AFRL/VS from the Defense Advanced research Program Agency (DARPA) Contract No. F29601-97-K-0010. In addition, I would particularly like to thank Lt. Col. James Shoemaker at DARPA for his continued support.

Last, but not least I would like to acknowledge the support of my dear friends Ebru Gokdag, Kalina Galabova, and Maryam Rahimi who listened when I needed to be heard. Thank you.

Table of Contents

Table of Figures

List of Tables

“To follow knowledge like a sinking star,
Beyond the utmost bound of human thought”
-- *Alfred Tennyson (1809-1892)*

Chapter 1

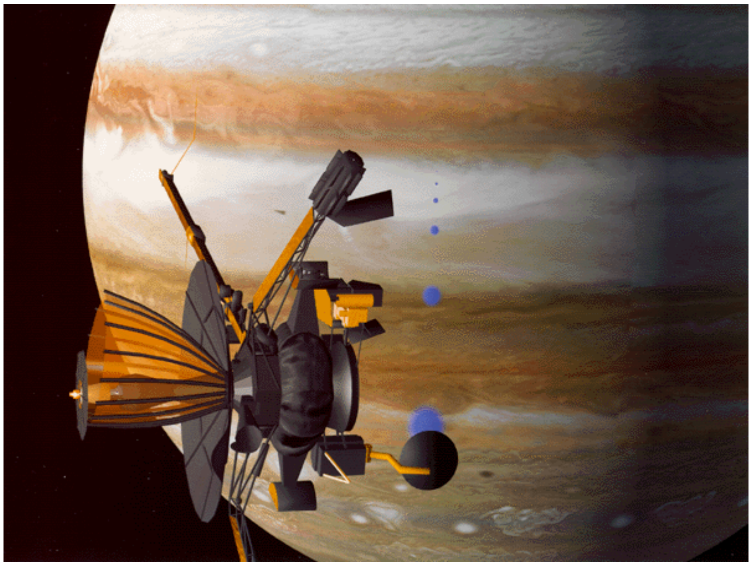
“Change alone is eternal, perpetual, immortal”
--Arthur Schopenhauer, German Philosopher

1. Introduction

> *“ September 21st, 2003: At 3:42 p.m. with roughly seven minutes to go, Galileo will move from day to night as it passes into Jupiter's shadow, and, one minute later, it will pass behind the limb of the giant planet as seen from Earth. Only 9,283 kilometers above the clouds, the path of the spacecraft will take it out of sight of ground controllers. The last data ever to be received from the Galileo spacecraft will now been sent. The remaining few minutes of the craft will be spent in darkness. At approximately 3:49 p.m. (1949 GMT), Galileo will reach the end of its nearly 14-year odyssey.*” -NASA Press Release September 21, 2003

It was with these lines that the final chapter of the story of the Galileo spacecraft came to a closure. For those not familiar with the previous events in the life of the space probe, this press release exhibits little significance other than the end of yet another successful NASA mission. Yet for the engineers and scientists who had sat through the challenging early years of the Galileo mission, this press release was a marker for extraordinary achievement.

It all began in 1989, when following a launch by space shuttle Atlantis, Galileo embarked on its journey to probe Jupiter and its moons. The initial phases of Galileo’s mission went flawlessly, raising the spirits of the mission team who had worked so hard since the 1970s on the design, construction, and launch of the space probe. The enthusiasm however came to a screeching halt when on April 11, 1991 (eighteen months into its journey) a routine procedure to open its high-gain antenna (HGA) failed after having been tested on Earth years before. The HGA was the main payload of the spacecraft, with the function of sending images of Jupiter when the spacecraft reached its destination. With the HGA useless, the entire $1.39 billion of investment seemed lost.



In the confusion that ensued, the engineering team proposed many suggestions to force the HGA open. All of them failed. Eventually, team members had a wild idea: extensively reprogram Galileo's onboard computers for better handling of data and increased data compression, upgrade the capabilities of ground tracking stations, and relay the data through Galileo's low-gain antenna (LGA). The plan was brilliant, and took from 1993-96 to complete. The ability of the Galileo design respond to changing conditions in the face of partial failure resulted in one of the most dramatic comebacks in recent space history. Not only did Galileo achieve its primary mission, but it also provided a plethora of unparalleled scientific data in its extended mission. The existence of a combination of hardware and software components that were flexible for modification, change of function and upgrade enabled this success. The process of reconfiguring Galileo's hardware and software is not unlike the ability of the human brain that reroutes some abilities from dysfunctional organs to healthy ones when the need arises.

This ability to adapt to changes in the environment unforeseen in the design of an organism or artifact is called *flexibility*. Flexibility has been defined differently in many fields of engineering, architecture, biology, economics, etc. In the context of this dissertation, we define flexibility as *the ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost-effective manner*. Thus, flexibility is the ease with which the system can respond to uncertainty in a manner to sustain or increase its value delivery. It should be noted that uncertainty is a key element in the definition of flexibility. Uncertainty can create both risks and opportunities in a system, and it is with the existence of uncertainty that flexibility becomes valuable.

Flexibility in Space Systems

In this dissertation, we focus on flexibility within the context of space systems. Space systems are extremely delicate and costly engineering artifacts that take a long time to design, manufacture, and launch into space and after they are launched, there is limited access to them. Millions of Dollars of space systems assets are lost annually, when the space system fails to meet new market conditions, cannot adapt to new applications, its technology becomes obsolete or when it cannot cope with changes in the environment it operates in. With the long time it takes to design, build and launch a spacecraft, often the conditions for which the spacecraft was first designed have changed shortly after its launch. Functional requirements can change, opportunities for using the spacecraft for new tasks can arise, and failures may prevent the spacecraft from functioning adequately.

The existence of flexibility can help the spacecraft adapt itself to the change at hand, or even take advantage of new possibilities while in space. Therefore integrating flexibility into the design of space systems is valuable.

Problem Definition: Measuring the Value of Flexibility in Space Systems

While everyone would agree that flexibility is useful, *in the absence of a way to measure its value, most decision-makers overlook its implementation in their space systems*. Building flexibility into a system normally requires an additional upfront investment that has to be justified; otherwise, it will often be the first item on the list of items that are crossed out in a budget cut for a large project. The existence of a framework for measuring flexibility is thus desirable and necessary for its consideration as part of spacecraft design and operation.

While the literature is not lacking in number of flexibility measures provided for different types of systems and different aspects of flexibility within those systems, there is a void for a unified framework for measuring the multiple aspects of flexibility in space systems. This research is an effort to provide such a framework, based on the common fundamental elements that define the nature of flexibility in different aspects of space systems.

A single flexibility framework for space systems will allow flexibility to be considered in the design of the system from component level to architecture level, and makes it possible to compare across different flexibility options open to decision-makers that would otherwise not be possible with a multitude of frameworks based on different assumptions and varying forms.

A single flexibility framework can:

- enable consideration of different aspects of change in a unified framework
- enable consideration of monetary and non-monetary impacts of change in a system
- enable consideration of space systems flexibility in a multi-attribute trade exploration (MATE) process in the design phase
- provide comparison of different courses of action after a system has been fielded

Research Hypothesis

The *hypothesis* of this research is that a single flexibility framework that is based on a combination of elements that are common to many types of flexibility can provide decision-makers with the ability to value different aspects of flexibility within their space system, and enable the integration of flexibility in the design of space systems. The common elements of flexibility are system boundary, time window of change, flexibility aspect, system accessibility, uncertainty, and responses to change in the value delivery of the system.

Research Methodology

In order to identify elements common to different types of flexibility, we explore the literature on flexibility with regards to space systems and other engineering systems. In particular, we look at more than 25 major papers in the field of space systems flexibility, more than 60 papers in the field of manufacturing flexibility and 43 papers in the field of systems engineering. Through this extensive literature review, we will explore how different types of flexibilities are defined and measured in technological systems, and what factors affect their value. We will then proceed to establishing a framework based on the common elements of flexibility found in the literature and explore the influence of these elements on the nature and value of flexibility. We will then apply the framework to different case studies involving different types of space systems and explore the value of varying aspects of flexibility within these systems with the proposed flexibility framework and explore its usefulness in integrating flexibility into the design process.

Structure of the Dissertation

The content of this dissertation is divided into three parts which contains literature review, extraction of element of flexibility and synthesis of a general framework, and a series of case studies. Figure 1.1 shows the flow of the chapters in this dissertation. A brief description of each chapter is presented here.

In Chapter 2 we look at a subset of literature in the field of engineering systems. The majority of the papers and research in the field of engineering systems are divided into two major subgroups, which represent the manufacturing systems flexibility and the network flexibility. The field of manufacturing systems has the richest amount of literature, and is presented first in the chapter. We present a set of theses definitions, classifications, and measurement of flexibility in the manufacturing systems. Next, definitions in the field of network flexibility are presented. The concept of network flexibility is tightly coupled with the concept of network complexity. Therefore, a set of definition and various measures and metrics for flexibility and complexity in network-based systems are extracted from the literature and presented in Chapter 2.

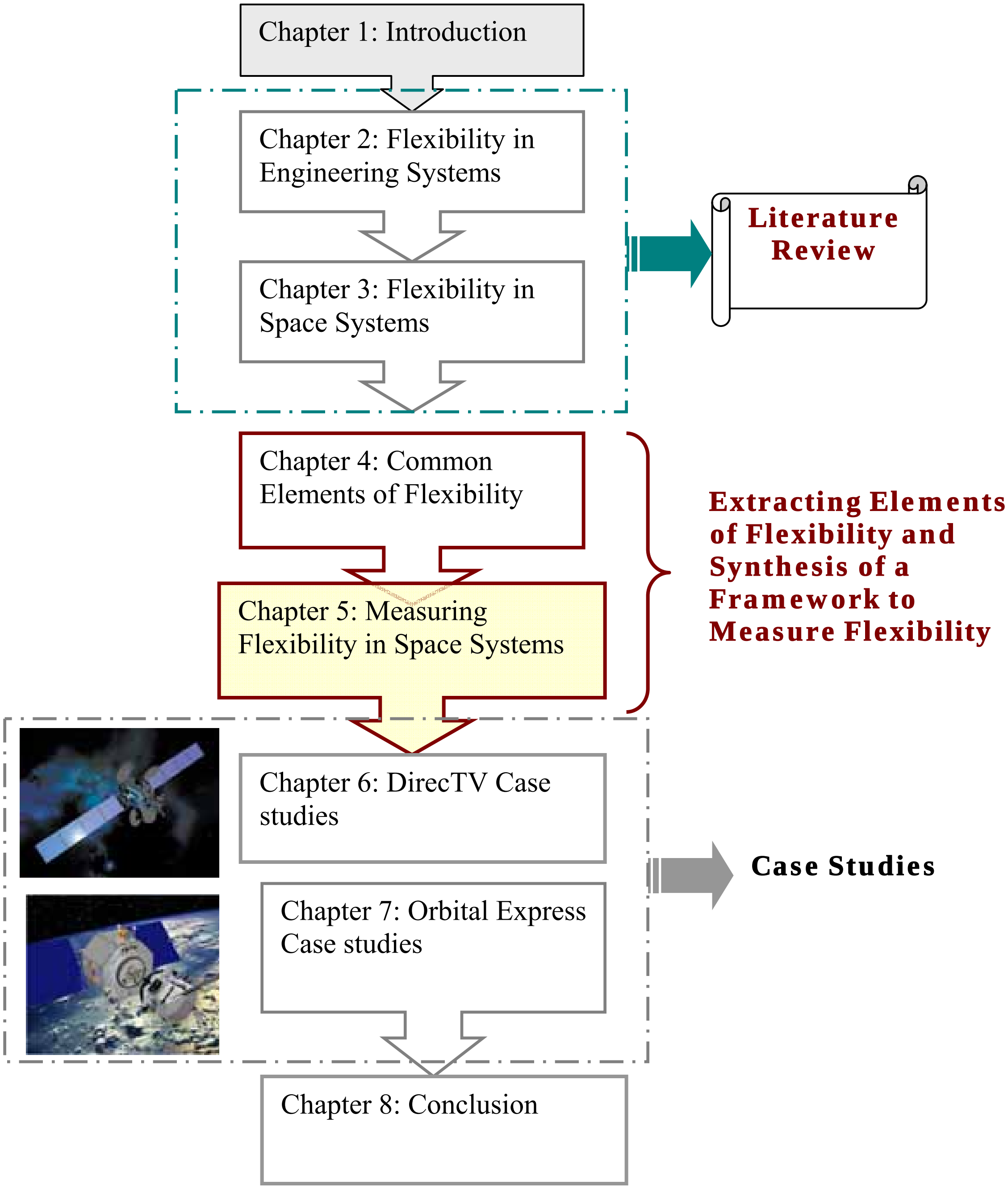


Figure 1.1. The dissertation flow

In Chapter 3, we review the major research and papers in the field of space systems engineering. The research on flexibility is a relatively a new field in space systems engineering. Different definitions, concept, metrics, and measures of flexibility in space systems are presented from the literature in this chapter. We identified the contributions, shortcomings, and limitation of each metric and framework. The majority of the defined measures in space systems are coupled with the field of economics and real options theory.

In Chapter 4, we focus on extracting the elements of flexibility from the previous literature review chapters, with a focus on space systems flexibility. We identify the six elements of flexibility to be the chosen system boundary, aspect of flexibility, time window of change, uncertainty, access, and the system's response to change in its value delivery. We describe each element in details with a set of examples following each element of flexibility.

In Chapter 5, we suggest a framework to measure flexibility in space systems. The framework is named 6E (six-element) flexibility framework which incorporates all the six elements identified in the previous chapter. The framework consists of twelve steps and each step is described in details following some examples.

Chapter 6 presents the first case study chapter, which looks at two different aspects of flexibility in a commercial space system. We choose DirecTV Group and its satellite assets as an example of a commercial space system. The first case study within this chapter looks at a set of alternatives of design and decisions that can create flexibility in DirecTV-8 satellite. The flexibility associated with each suggested alternative is measured and compared to the baseline case using our suggested 6E flexibility framework. The second case study within this chapter looks at a fleet of DirecTV satellites and a set of suggested alternatives to create flexibility in his system. The flexibility associated with each alternative is also measured using the suggested framework.

Chapter 7 deals with the second case study, which incorporated scientific, military, and commercial space systems. The chapter includes two case studies, which revolve around the major future space system infrastructure: the DARPA's Orbital Express program. The first case study looks at a possible architecture of the Orbital Express program in sun synchronous orbit with one military and two scientific client space systems. A set of alternatives are suggested to provide services to these client satellites and the value of flexibility associated with each alternative is measured. The second case study looks at a hypothetical Orbital Express infrastructure in geosynchronous orbit. A set of commercial space systems, Milstar satellites, and the James Webb space telescope are considered as the clients of such an infrastructure. We look at a set of alternatives consisting of different architectures of the infrastructure and decisions and we measure the flexibility associated with each alternative using the suggested 6E flexibility framework.

Chapter 8 includes the conclusion of this dissertation. A summary of the dissertation, key insights, contributions of this dissertation and implications for the designing flexibility in space systems are presented and a set of future works are suggested.

In the next Chapter, we will look at the concept of flexibility within the context of engineering systems.

Chapter 2

"Men are born soft and supple; dead, they are stiff and hard. Plants are born tender and pliant; dead, they are brittle and dry. Thus whoever is stiff and inflexible is a disciple of death. Whoever is soft and yielding is a disciple of life. The hard and stiff will be broken. The soft and supple will prevail."
-- *Lao-tzu, 6th century B.C. Chinese philosopher, founder of Taoism*

2. Flexibility in Engineering Systems: A Literature Review

ENGINEERING systems are human-designed technology-centered systems that are composed of interacting components and serve a given purpose (Moses 2004). Such systems include aerospace systems, transportation systems, infrastructure systems, telecommunication systems, manufacturing systems, and many other systems that are complex and large-scale. While many of the traditionally important design aspects of such systems have focused on cost, function, and performance, there is an increasing emphasis on the value of *flexibility* as an important long-term attribute of these systems.

2.1. Flexibility in Engineering Systems

Engineering systems flexibility becomes important when design shifts from a point-design perspective to a lifecycle design perspective. With many engineering systems operating under uncertain conditions and emerging requirements, interest in the ability of such systems to provide functionalities other than those originally specified has increased. In this chapter, we will look at the literature of flexibility as applied to manufacturing systems and network-based systems such as telecommunications, energy, and transportation.

2.2. Manufacturing Systems Flexibility

Among the various engineering systems, manufacturing systems have been the most fertile ground for the design and implementation of flexibility. The literature on manufacturing flexibility is by far the richest among all engineering systems. The large number of publications is mainly caused by the rapidly changing markets of today, which have resulted in constantly changing customer requirements, putting pressure on the manufacturing sector to modify its products constantly. Numerous papers discuss the different aspects of flexibility within manufacturing systems and include definitions, classifications, measurements, and the need for flexibility. We will start with the definitions of flexibility in manufacturing systems.

2.2.1. Definitions

Flexibility in manufacturing has been defined as a characteristic of the interface between a system and its external environment (Correa 1994). Flexibility can be viewed as a filter, buffering the system from external perturbations. Flexibility thus functions as an absorber of uncertainty. The external perturbations can be characterized by measure, frequency, novelty, and certainty (De Toni and Tonchia 1998).

Slack (1987) describes flexibility using a value range or number of states reachable. He defines flexibility as:

- The range of possible states;
- The time needed to move from one state to another;
- The cost required to change the state.

Whitney (2000) argues that flexibility comes in many forms and that there is no single definition that fits all circumstances. In addition, “flexibility often comes with negative side effects such as loss of efficiency due to learning, changeover, extra management oversight, and so on.”

Upton (1995a) considers flexibility to involve various dimensions, each of which appears for different time intervals and has three elements, which are range, mobility (in relation to the transition penalties for moving within the range), and uniformity (of aspects other than cost within the range). Flexibility is therefore defined as “the ability to change or react with little penalty in time, effort, cost, or performance.”

According to Zelenovich (1982), flexibility is the ability of a manufacturing system to adapt to changes in environmental conditions and in process requirements. The importance of this definition is that, for the first time, it takes into account both the market’s demand and the exploitation of the opportunities offered by technological innovations. Flexibility in manufacturing is called for because of the variability of demand (random or seasonal), shorter life cycles of products and technologies, wider ranges of products, increased customization, and shorter delivery times.

There are many more definitions of flexibility with a focus on organizational and managerial flexibility, which have not been discussed here because of their lack of relevance to the current research.

2.2.2. Classifications of Flexibility in Manufacturing

De Toni and Tonchia (1998) classify manufacturing flexibility using the following logic:

- Horizontal, or by phases, refers to the single manufacturing stages, and, in a wider sense, to all the phases that constitute the value chain.
- Vertical, or hierarchical, refers to the degree of detail of the analyzed object. Flexibility can be estimated in relation to the individual resources of a system (micro level) or to the whole system (aggregate flexibility, or macro level) (De Toni and Tonchia 1998).
- Temporal: Zelenovich (1982) was the first to consider short-term or adaptation flexibility, as well as medium- to long-term flexibility. More detailed temporal classifications also exist in the field of manufacturing.
- By the object of the variation. This is the most common classification in the literature.

Browne et al. (1984), taking into account flexible manufacturing systems (FMS), define eight different types or dimensions of flexibility:

1. Machine flexibility: The ease of change to processing a given set of part types
2. Product flexibility: The ability to change to process new part types. It can be measured by the time required to pass from one mix of parts to another.
3. Process flexibility: The ability to produce a given set of part types.
4. Operation flexibility: The ability to interchange ordering of operations on a part.
5. Routing flexibility: The ability to process a given set of parts on alternative machines.
6. Volume flexibility: The ability to operate profitably at varying overall levels. This type is measured by the volume increase/decrease that causes the average costs to reach the maximum acceptable value.
7. Expansion flexibility: The ability to easily add capability and capacity. This is determined by the dimensions in terms of capacity that the system can reach.
8. Production flexibility: This refers to the universe of part types that can be processed. It is defined as the potential mix of the parts that can be produced (Browne et al. 1984).

2.2.3. Measurements of Flexibility

The importance of flexibility has created a major impetus in the field of manufacturing systems to design ways for measuring flexibility. Measuring flexibility is still an under-developed subject. As defined by Shewchuk (1999), a flexibility measure is a “formula, algorithm, methodology, or the like, for generating a value for a given flexibility type under given conditions.”

Sethi and Sethi (1990) assert that various proposed measures are somewhat naive and arbitrary. “In spite of the need, no well-accepted operationalizations exist” (Gerwin 1993).

Chen and Chung (1996) argue that only very limited work has been done on investigating the robustness of the suggested measurements.

As with space systems, given the difficulties in measuring manufacturing flexibility, it is financially difficult to justify the additional cost for implementing flexibility in the system. Selected literature on existing measures is briefly reviewed here.

Kumar (1987) presents an information theory view on manufacturing flexibility and introduces a measure based on information theories, derived from thermodynamics. The measure is based on markovian analysis of the interrelationship between machines in the manufacturing system. The formula is presented as follows:

$$F = -\sum_{i=1}^{n} q_i \ln q_i \qquad (2.1)$$

where q_i is the probability of a product going to visit next machine i, and n is the number of machines in the system.

Brill et al. (1989) present measures that quantify how well a manufacturing system can absorb changes in the environment. They define different tasks in manufacturing systems and assign weights to each task. They define the flexibility of a machine, flexibility of a group of machines, optimistic measure, pessimistic measure, Hurwitz type measure, mix measure of group and redundancy measure of group flexibility. They introduce the notion of *inherent flexibility*, as an unintentional attribute of a manufacturing system. Brill formulates the following flexibility measure of machine M relevant to task S as follows:

$$F_{M,S} = \int_{t \in S} \frac{e(M,t)dW(t)}{W(S)} \qquad (2.2)$$

where e is the effectiveness and capability of a machine, S is the task set, t is a member of the task set S, W is the weight of importance associated with each task.

Zahran et al. (1990) quantify routing, product, volume, and expansion flexibilities. In designing these measures, they focus on the alternatives for processing each product and the efficiency of the system in adapting itself to process new products. Some of their suggested measures are presented as follows:

$$F_r = \frac{1}{n.m} \cdot \sum_{i=1}^{\infty} \left(\frac{1}{O_i} \sum_{k=1}^{O_i} \sum_{j=1}^{O_i} \left(E_{ij}^k \cdot A_j \right) \right) \tag{2.3}$$

where F_r is the routing flexibility, E_{ij}^k is the efficiency of performing operation k of product i on machine j, A is the availability, O_i is the number of processing operations for product i, m and n are the number of products and machines respectively.

$$F = \sum_{p=1}^{n} \sum_{q=1}^{n} \frac{X_{pq}}{n^2} \tag{2.4}$$

where F is the material handling flexibility, n is the number of machines, and X_{pq} is defined to be one if machine p and q are connected by a handling mean and zero otherwise. Kochikar et al. (1992) develop measures of flexibility based on state-transition formalism, the reachability graph. A reachability graph (RG) is a structure that represents the discrete states of a system and the transitions between them. Each flexibility measure lies between 0 and 1 and assumes a value of unity for a situation of maximum flexibility.

Benjaafar et al. (1992) classify manufacturing flexibility as product-based or process-based and present a set of entropy-based formulas for each measure. They introduce four types of process flexibility, which include processor, mix, volume, and expansion flexibility. A sample of four suggested entropy-based measure is as follows:

$$\Phi(q) = -\sum_{t_i \in T_q} \chi_i \log(\chi_i) \tag{2.5}$$

where

$$\chi_i = \frac{e_i}{\sum_{t_i \in T_q} e_i}$$

$\Phi(q)$ is a measure of flexibility of a processor q, T_q is the set of tasks that are performable on processor q, e_i is the effectiveness of performing task i on processor q.

Benjaafar (1994) further investigates the relationship between flexibility and performance of manufacturing systems. Conditions under which a positive correlation between flexibility and performance exists are identified and the characteristics of this correlation are described. He introduces two models, one based on the product waiting time and the other on probability of waiting.

Gupta et al. (1992) perform an empirical examination of trade-offs in a flexible manufacturing system (FMS). They identify different flexibility types and show that there is a trade-off between them. In a later paper, Gupta (1993) proposes that any measure must inevitably depend on factors such as the degree of uncertainty in the environment, management objectives, machine capabilities, and configuration. He proposes a model to evaluate flexibility when a firm needs to choose the number of machines and the size and flexibility of each machine. In this paper, machine-, cell-, plant-, and corporate-level flexibilities are being studied.

De Groote (1994) proposes a framework based on the identification of the set of technologies, environments, and performance criteria. He characterizes flexibility and diversity as complementary properties. Suarez et al. (1995) also make progress toward a framework by defining types of flexibility and examining the relationship among them through a study of thirty-one plants in the printed circuit board industry. According to Fine's classification scheme, there are four concerns in modeling literature:

1. Flexibility and life cycle theory;
2. Flexibility as a hedge against uncertainty;
3. Interaction between flexibility and inventory;

4. Flexibility as a strategic variable that influences competitors' actions.

They also define some relationships between different flexibility types.

Chen et al. (1996) investigate the relationship between flexibility measurements and system performance in a flexible manufacturing system environment. They develop formulas for calculating machine flexibility and routing flexibility. The machine flexibility formulas are defined as weighted and unweighted. The routing flexibility formulas are defined as potential and actual routing flexibility, and routing flexibility utilization. The proposed measures by Chen et al. are as follows:

$$UMF_j(\Omega) = \frac{\mu_j}{|\Omega|} \tag{2.6}$$

where $UMF_j(\Omega)$ is the unweighted machine flexibility of machine *j*, Ω is a set of operations to be processed in manufacturing systems, and μ_j is the number of operations that machine *j* can perform.

$$WMF_j(\Omega) = \sum_i w_i e_{ji} \tag{2.7}$$

where $WMF_j(\Omega)$ is the weighted machine flexibility of machine *j*, w_i is the weight of importance, and e_{ji} is the machine operation efficiency.

$$PRF(\pi) = \frac{\sum_h r_h}{H} \tag{2.8}$$

where $PRF(\pi)$ is the potential routing flexibility, π is a set of part types to be produced, H is the number of part types, and r_h is the number of feasible routs that part type h can flow through the system.

$$ARF(\pi)=\frac{\sum_h a_h}{H} \qquad (2.9)$$

where $ARF(\pi)$ is the actual routing flexibility, and a_h is the number of routs actually used by part type h to achieve a production planning objective.

$$RFU(\pi)=\frac{ARF(\pi)}{PRF(\pi)} \qquad (2.10)$$

where $RFU(\pi)$ is the routing flexibility utilization of a flexible manufacturing systems.

Nelson et al. (1997) investigates technology flexibility, which is the technology characteristic that allows or enables adjustments and other changes in the business process. The authors develop and validate a measurement model of technology flexibility. Constructs and definitions of technological flexibility are developed by examining the concept of flexibility in other disciplines and the demands imposed on technology by business processes.

DeToni et al. (1998) and Beach et al. (1998) perform a comprehensive literature review of manufacturing flexibility. The literature on manufacturing flexibility is analyzed according to a scheme that considers six different aspects: definition of flexibility; request for flexibility; classification in dimensions of flexibility (horizontal, vertical, temporal, by the object of the variation, mixed); measurement of flexibility; choices for flexibility; and interpretation of flexibility.

Choi et al. (1998) identify three limitations for manufacturing flexibility measures; ambiguous definitions of flexibility, interdependence among various types of flexibility, and mixed use of available and realized flexibility. They propose a new concept of flexibility called comprehensive flexibility. It is an integrated performance measure that covers various types of flexibility in manufacturing systems. Their measures is based on evaluating total inefficient time, total available machine time, total processing time, and total flow time. Choi et al. flexibility measures are as follows:

$$PMCF_M = 1 - \frac{T_{IM}}{T_{AM}}, \quad 0 \le PMCF_M \le 1 \tag{2.11}$$

$$PMCF_P = 1 - \frac{T_{IP}}{T_{FT}}, \quad 0 \le PMCF_P \le 1 \tag{2.12}$$

where $PMCF_M$ is the performance measure of flexibility in machine, $PMCF_P$ is the performance measure of flexibility in parts, T_{IM} is the total inefficient time in machines , T_{IP} is the total inefficient time in parts, T_{AM} is the total available machine time, and T_{FT} is the total flow time.

Parker et al. (1999) introduce a framework to facilitate the development of flexibility measures. Measures of various flexibility types are drawn from the literature and compared with the purposes and criteria of the flexibility types, and the best measures are presented. One suggested measure is as follows:

$$VF = 1 - \frac{F}{C_{\max}}\left(\prod_{i=1}^{n} \frac{a_i}{b_i}\right) \tag{2.13}$$

where VF is volume flexibility, C_{max} is the maximum capacity of the system, a_i is the number of capacity units required per part produced, b_i is the contribution margin for the product, and F is the fixed operating cost.

Shewchuk et al. (1998) identify three shortcomings in attempts to develop flexibility terms for manufacturing. They develop a framework for modeling the manufacturing system and its environment, flexibility types and measures, and a classification scheme for flexibility terms. Furthermore, Shewchuk (1999) proposes general flexibility measures for manufacturing application. The author presents ten generic flexibility measures, which are derived from five different processing scenarios. Shewchuk following suggested measures are for a case where the benefit is obtained when the item is processed:

$$F_{11} = \frac{\sum_{i=1}^{N} f(m_i) p_i}{\sum_{i=1}^{N} f(i) p_i} \tag{2.14}$$

where

$f(k) =$

- Constant, if benefit increases at a constant rate as *k* increases;
- Monotone decreasing, if the benefit increases at a decreasing rate as *k* increases
- Monotone increasing, if the benefit increases at a increasing rate as *k* increases
- Zero, if $k = 0$

F is the generic flexibility measure, *i* is the number of arriving item, *N* is the total number of items, p_i is the probability of arrival and processing of item *i*, *f(k)* is the benefit function, and m_i is the location in processing sequence of item *i*.

Shewchuk's other suggested measure based upon performance in processing the items is as follows:

$$F = \frac{\sum_{i=1}^{M} [f(\lambda_i) - f(LB(\lambda))] p_i}{[f(UB(\lambda)) - LB(\lambda)] \sum_{i=1}^{M} p_i} \tag{2.15}$$

where

$f(\lambda) =$

- Monotone increasing at a constant rate, if benefit increases at a constant rate as λ increases
- Monotone increasing at a decreasing rate, if the benefit increases at a decreasing rate as λ increases
- Monotone increasing at a increasing rate, if the benefit increases at a increasing rate as λ increases
- Zero, if $\lambda = 0$

F is the generic flexibility measure, i is the number of arriving item, M is the total number of items, p_i is the probability of arrival and processing of item i, λ is a continuous variable which indicates performance in processing, UB and LB are the upper and lower bound functions of the performance.

Using these general measures, Shewchuk fits the product, routing, input, material handling, and mix flexibilities into his flexibility formulas. In defining flexibility, he considers many important variables such as probability, performance, and benefit obtained from item processing. Building on their previous work, Shewchuk et al. (2000) investigate the effects of manufacturing system design on product, mix, production, and volume flexibilities, and on trade-offs between these flexibility types, for different product environments. They develop four system-level flexibility types and measures: product flexibility, mix flexibility, production flexibility, and volume flexibility. Some of these measures are introduced as follows:

$$F_{PROD} = \frac{\|P'\|}{\|P\|} \tag{2.16}$$

where F_{PROD} is the product flexibility measure, P is a set of products, and P' is the larger subset of P. Product flexibility is defined as the ability of the system to cope with changes in products. Therefore, the product flexibility equal to one shows the maximum flexibility.

$$F_{MIX} = -\frac{\sum_{k=1}^{N} f_{MIX_k}}{\sum_{k=1}^{N_{PN}} b_k} \tag{2.17}$$

where

$$f_{MIX_k} = \left(\frac{\sum_{j=1}^{N} a_{jk} \left(\lambda_{jk}^{*} - d_k / m_k \right)^2}{m_k} \right)^{1/2} \qquad \text{if } m_k \succ 1, \text{ otherwise zero}$$

$b_k = 1$ if $m_k \succ 1$, otherwise zero

$$d_k = \sum_{j=1}^{N} \lambda_{jk}^{*}$$

$$m_k = \sum_{j=1}^{N} a_{jk}$$

a_{jk} is a function of j and k mix if it is possible, λ_{jk}^{*} is the maximum production capacity for production scenario (j,k).

Kahyaoglu et al. (2002) identify a major drawback in formulating flexibility in previous literature, which is the need for determining the relevant probability distributions associated with uncertainty. They suggest formulas based on adverse and favorable changes in the environment. For example, the value of flexibility in the case of adverse change is perceived as a percentage reduction in performance degradation relative to the size of the impact caused by the change. The suggested formulas are as follows:

$$FV_i = \frac{\left(P_{i,s} - P_{i,o}\right)}{\left(P_{i,s} - P_{b,o}\right)} \quad , \ 0 \prec FV_i \prec 1, \text{ (adverse changes)} \qquad (2.18)$$

$$FV_i = \frac{\left(P_{i,s} - P_{i,o}\right)}{\left(P_{b,o} - P_{i,o}\right)} \quad , \ 0 \prec FV_i \prec 1, \text{ (favorable changes)} \qquad (2.19)$$

where FV_i is the flexibility of a manufacturing system given environmental situation i, $P_{b,o}$ is the level of performance when an optimal managerial action o is taken in base environmental situation b, $P_{i,o}$ is the level of performance when an optimal managerial action o is taken following the change from base environmental situation to a new situation i, and $P_{i,s}$ level of performance when base case managerial action is kept unchanged following a change from base case to a new environmental situation i.

Zhang et al. (2003) have classified the literature on manufacturing flexibility and the basis of competence and capability theory. They describe a framework that explores the relationships among flexible competence (machine, labor, material handling, and routing flexibilities), flexible capability (volume flexibility and mix flexibility), and customer satisfaction. They then develop valid and reliable instruments to measure the sub-dimensions of manufacturing flexibility, and apply structural equation modeling to large-scale samples. Beskese at al. (2004) have also provided a comprehensive literature review of more up-to-date measures of flexibility for manufacturing systems.

A review of the current literature in manufacturing shows that the suggested measures for flexibility are numerous, and often limited in scope. Most of these measures are not general and only have application for a very specific measurement purpose. Most are not applicable across different fields of engineering. Some are abstract (entropic approach to the flexibility), and most of the others measure only specific attributes of flexibility e.g., time, a specific change in functionality, cost, and so on. Still, there is much commonality with the types of flexibilities that are sought in space systems.

2.3. Network Flexibility

Many engineering systems are network-based. That is, they consist of a set of nodes and links connecting those nodes, with information, matter, or energy flowing through the different nodes from origins to destinations. With many recent events such as the 9/11 attacks, the national grid blackouts, and fears of cascading failures of telecommunication and information networks, the concept of flexibility in networks has recently gained more attention in the literature. Here we will look at some current efforts that focus on network-based flexibility.

2.3.1. Definition

The network view on flexibility has been introduced by Moses (2003) as follows: "A system is flexible if it is relatively easy to make certain classes of *changes* to it. A key goal of flexibility is to make it easier to *add new function*, or to *modify existing function*.

Flexibility can be viewed as an active and largely external approach to managing change. A human designer, user, or operator makes the changes in a flexible system."[1]

Looking through this lens at network systems, network flexibility comes into play when we can add *new* nodes and/or connect to existing nodes using alternate paths.

The basic assumptions in this definition of network flexibility are as follows:

- Most changes in the system are small.
- There are numerous such changes in a given period.
- The changes to the system are associated with relatively small costs.
- The links or paths of the system have the same value.

On the basis of the above assumptions, the network definition of flexibility is not very effective for systems under the following conditions:

- Changes are relatively few in a given period of time and their magnitude is relatively large.
- There are relatively large costs associated with changes to the system.
- The values of links in the system are heterogeneous.

In the network definition of flexibility, it can increase in an architecture at the *cost* of increasing the structural complexity[2]. From this, we can deduce that complexity is considered as a type of cost to the system. A flexible architecture is the one that allows for the expansion of links (benefit) with relatively low additional complexity (cost).

In this view of flexibility, one way of dealing with uncertainty is to have built-in flexibility in the initial design. Through built-in flexibility, one can make *various choices* at relatively *low cost*. The economic theory of real options may be used to analyze the cost of such alternatives. Moses (2002) believes that there may be some loss relative to an optimal solution due to the provision of options, but the cost is likely not prohibitive. He believes that in most cases the advantage of flexibility in dealing with change outweighs the performance loss.

---

[1] Joel Moses, "The Anatomy of Large Scale Systems", April, 2002

[2] Kolmogorov defines complexity as the length of the shortest description of the system.

2.3.2. Flexibility and Robustness in Network Systems

According to Moses (2003), network systems are by nature quite flexible. In the telephone network, for instance, there are multiple paths that connect two nodes. Hence, if one line cannot be used or is congested, it becomes possible to use alternative paths in the system to reach the other node. In networks, it is usually also possible to increase the total number of paths, thereby increasing the flexibility and robustness of the overall system. Moses distinguishes here between robustness and flexibility. He defines robustness as the ability to get around failing nodes and still maintain most of the original system function. Flexibility is the ability to add new nodes and connect to existing nodes using alternate paths, thereby increasing the original functionality of the system. A flexible system will thus likely be robust as well, if the changes needed for robustness are ones easily implemented using the system's flexibility. Changes in the system configuration allow for the installation of new paths, and such a system-wide change can be indicative of the system's overall flexibility (Moses, 2003).

The network-view of flexibility yields different perspectives in information-centric vs. mass/energy-centric systems[3]. Through the network flexibility definition, the information-centric systems show higher flexibility in comparison to mass/energy centric systems. In information-centric systems, such as communication systems or large-scale software systems, the potential for scaling the size and/or performance of the system by several orders of magnitude exists. One such example cited by Moses is the number of bits being transmitted by optical communication systems, which has increased by several orders of magnitude in just the past two decades without the physical infrastructure experiencing the same growth. Such scaling is easier in information centric systems than in mass/energy-centric systems, which have not tended to have such increases in performance. An example that is given in the case of transportation systems is the fact that three to ten fold increases in transportation speeds have been considered revolutionary whenever they occurred within the past several centuries (Moses, 2003).

---

[3] Joel Moses, "Foundational Issues in Engineering Systems: A Framing Paper", March 29-31, 2004.

2.3.3. Measuring Network Flexibility

With regards to measuring network flexibility, Joel Moses believes that a system possessing a great range of alternate paths allows for a significant increase in additional paths with a small increase in the number of interconnections through additions of new nodes or modifications of existing ones. He defines the flexibility of a system as the number of paths within it, counting loops just once. The higher the numbers of such paths, the more choices there will be in the system, making the system more flexible. Still, new paths and new nodes can also mean increased complexity, which are considered a cost (Moses 2003). A brief review of existing measures of complexity for a network follows in this Chapter.

In order to analytically express the above-mentioned definition of flexibility, we start with a simple example of a network. Suppose that mass, energy, or information is being transferred between nodes. Network A has N_1 paths or links and n_1 nodes. Network B has N_2 links and n_2 nodes. Network A can be called flexible if, for a relatively small cost and/or complexity, it can be expanded, e.g., to network B. If Network A cannot be expanded with relative ease, the network is not flexible. Many physical networks have physical limitation to expansion (the number of links cannot increase) or adding more links is associated with a large cost in the system. The schematics of the two mass/energy/information networks A and B can be seen in Figure 2.1.

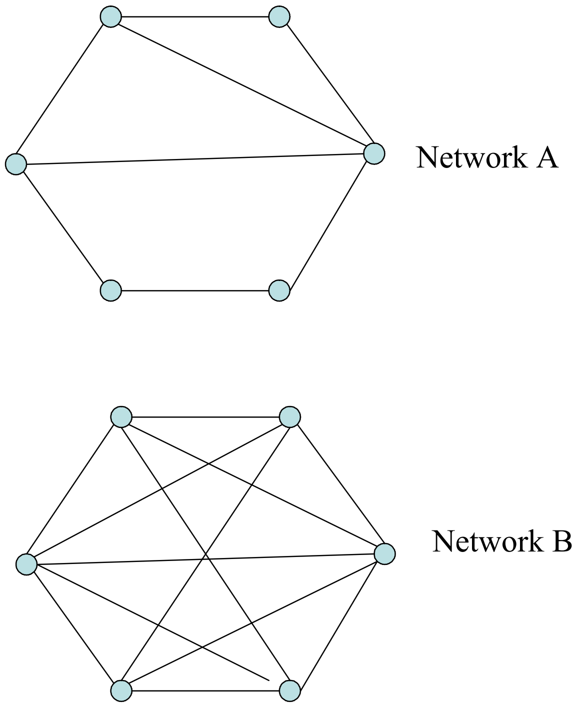


Figure 2.1. A schematic of simple networks A and B

One related way of measuring flexibility is to count the number of distinct paths in the system divided by the number of nodes (Magee and De Weck 2002). The model of a system as connections between nodes or components and paths between such nodes is especially important in information systems, but it is useful in discussions of most infrastructures. Then the relationship can be shown as:

$$Flexibility\_measure = \frac{N_{Paths}}{n_{nodes}} \qquad (2.20)$$

where

N_{Paths} = # of distinct paths in the system

n_{nodes} = # of nodes

With regards to network flexibility, the following can be observed:

- One of the most important aspects of flexibility in networks is *expansion*. Then the flexibility of a network is measured with respect to expansion.
- The suggested metric by and De Weck (2002) which is number of paths or links per node, can be viewed as the level of goodness or positive outcome, or benefit of the network system.
- Complexity can be treated as a type of cost in network systems. The network expansion is also associated with real cost (monetary costs) in most physical networks.
- A network is flexible when it can expand from one state to another with relative ease. Thus flexibility can only be measured when changes occur in the system, and could be considered a latent capability of the system.
- We can compare the possible expanded networks to the original state of the network and evaluate the degree of flexibility. Network flexibility can thus be measured as follows:

$$F_{Network\_Expansion} = \frac{\left(\dfrac{Flexibility\_measure_{Expanded\_state}}{C_{Expanded\_state}}\right)}{\left(\dfrac{Flexibility\_measure_{original\_state}}{C_{original\_state}}\right)}$$

→ Expanded
State of the
Network

→ Original
State of the
Network

- The network expansion flexibility formula can be rearranged to the following form:

$$F_{Network\_Expansion} = \frac{\left(\dfrac{N_{Expanded\_state}}{n_{Expanded\_state}}\right)}{\left(\dfrac{N_{Original\_state}}{n_{Original\_state}}\right)} \cdot \frac{C_{Original\_state}}{C_{Expanded\_state}} \qquad (2.21)$$

where

$F_{Network\_Expansion}$ = Flexibility of a network with respect to expansion

$\dfrac{N_{Expanded\_state}}{n_{Expanded\_state}}$ = Number of links per node for the expanded network

$\dfrac{N_{Original\_state}}{n_{Original\_state}}$ = Number of links per node for the original network

$C_{Original\_state}$ = Cost of the original network

$C_{Expanded\_state}$ = Cost of the expanded network

2.3.4. Quantitative Measures of Network Complexity

Complexity plays an important role in evaluating network flexibility according to Moses (2003). Therefore, in this section, a brief overview of complexity measures is presented. The measures of complexity in different fields can be organized into major groups based on difficulty of description, difficulty of creation, and degree of organization (Lloyd, 2003). The complexity measures, which are dealing with difficulty of description, are typically measured in bits[4]. The complexity measures, which are dealing with difficulty of creation of the system, are typically measured in time, energy, dollars, etc[5]. The complexity measures related to degree of organization can be divided into two quantities: difficulty of describing organizational structure, whether corporate, chemical, cellular, etc. and amount of information shared between the parts of a system as the result of this organizational structure[6].

According to Bonchev, networks are well characterized as structural patterns or motifs by graph theory. Graph theory has a history of more than 150 years as a branch of discrete mathematics. It was first conceived by Leonard Euler in 1788, who constructed a graph to solve the famous mathematical puzzle for the Königsberg bridges, a network problem that has analogies in transportation and telecommunications networks today(Bonchev and Buck 2000).

Graph theory is generally used to predict travel and transfer behavior over networks. Basically, in graph theory a network is defined by the set of V nodes, {V} ≡ {v1, v2, …,

---

[4] Examples of such metrics are: information, Entropy, Algorithmic Complexity or Algorithmic Information Content, Minimum Description Length, Fisher Information, Renyi Entropy, Code Length.

[5] Examples of such measures include Computational Complexity, Time Computational Complexity, Space Computational Complexity, Information--Based Complexity, Logical Depth, Thermodynamic Depth and Cost.

[6] Examples of these metrics are Complexity Metric Entropy, Fractal Dimension, Excess Entropy, Stochastic Complexity, Sophistication, Homogeneous Complexity, Grammatical Complexity, Algorithmic Mutual Information, Channel Capacity and so on.

vV}, and the set of E links lines, {E}≡{E1, E2, … , EE}. Different graphs are characterized by the pattern of their connections or their topology, not their geometry. A path in a graph is defined as a sequence of adjacent links between two nodes without traversing any intermediate node twice. The distance d_{ij} between nodes i and j is defined as the shortest path between them. For any graph G, the distance matrix D(G) is a square V x V matrix, depicting the d_{ij}s of every two nodes (Harray 1995).

It has been suggested that the complexity of a structure increases with its connectivity. There are however arguments that the complexity may initially increase until it passes through a maximum and then goes down to zero for complete graphs (that is graphs that where all the nodes are connected to each other) since complete graphs are describable in a simple, more abstract fashion. The latter view of complex comes from modifying Shanon's entropy of information measure to topological complexity. Looking at several papers Shanon's formula and its modified versions is a widely used measure for complexity in networks, particularly information networks and biological and chemical networks that are represented using graph theory (Bonchev 2000&2003). According to it, the entropy of information H(α) in describing a message of N symbols, distributed according to some equivalence criterion α into *k* groups of $(N_1, N_2, \ldots, N_k)$ symbols, is calculated according to the following equation:

$$H(\alpha) = -\sum_{i=1}^{k} p_i \log_2 p_i = -\sum_{i=1}^{k} \frac{N_i}{N} \log_2 \frac{N_i}{N} \text{ bits/symbol} \qquad (2.22)$$

where the ratio $N_i / N = p_i$ defines the probability of occurrence of the symbols of the i_{th} group.

Another approach to measuring complexity in networks is measuring the average adjacency and separation between nodes. It is suggested that networks with high complexity are characterized by both high node-node connectedness and small node-node separation. Therefore, in characterizing network complexity, once can measure the ratio $A/D = \langle a_i \rangle / \langle d_i \rangle$ of the total adjacency and the total distance of the graph (Bonchev and Buck 1995). This measure can change between 0 and 1, with 0 being the least complex system and 1 being the most complex system. This ratio is being modified and calculated through complicated mathematical expressions for different types of graphs (star graphs, canvass graphs, monocyclic graphs, polycyclic graphs, and complete graphs).

A rather easy metric to measure complexity in a network is the cyclomatic complexity measure proposed by McCabe (1996). Cyclomatic complexity, *V(G)*, applies graph theory to measure control flow complexity in software codes. The metric is the number of connected regions in a flowchart, for a subroutine with one entrance and one exit. McCabe's metric can also be calculated from the number of links and nodes in the flowchart. It is defined as:

$$V(G) = (\#Links) - (\#Nodes) + 1 \qquad (2.23)$$

While this can be easily applied to any network system, there is little physical meaning for systems other than software.

One other suggested way of measuring complexity is using information theory suggested by Moses (Sussman 2000). In this definition, a highly intricate set of interconnections contains much information, whereas a highly regular one contains far less. Moses claims that the complexity of a system simply as the number of interconnections between the parts or, the number of interconnections divided by the number of nodes.

The field of information theory contains many complexity measures. The information axiom defines a good design as the one that is decoupled and has minimal information content (summers and Shah, 2003). Some of these measures are presented as follows:

Real and imaginary complexity (Suh 2001):

$$C_R = \sum_{i=1}^{n} \ln\left|\frac{1}{P_i}\right| \qquad (2.24)$$

$$C_I = \ln\left(\frac{1}{P_{prob}}\right) \qquad (2.25)$$

where C_R and C_I are real and imaginary complexity of a problem; P_i is the probability of success for achieving the i^{th} functional requirement and P_{prob} is the probability of accidentally satisfying each functional requirement.

Summers and Shah Complexity measures (2003):
Most of these complexity measures are based on entropic measures and information content. Some of theses metrics are:

$$Cx_{size\_prob} = \{(M^0 + C^0) \times Ln|idv + ddv + dr + mg|\} \qquad (2.26)$$

where Cx_{size_prob} is the complexity of a problem based upon size.

$$Cx_{size\_art} = \{(M^0 + C^0) \times Ln|idv + ddv + dr|\} \qquad (2.27)$$

where Cx_{size_prob} is the complexity of a design based upon size.
and complexity of a problem based on process

$$Cx_{size\_process} = \{(M^0 + C^0 + P_{op}) \times Ln|idv + ddv + dr + mg + a_{op} + e_{op} + s_{op} + r_{op}|\} \qquad (2.28)$$

where
M^0 = Number of primitive modules available in a specific representation
C^0 = Number of relationships available between all available modules
idv = Number of independent design variables declared
ddv = Number of dependent design variables declared
dr = Number of design relations declared
a_{op} = Number of analysis operators
e_{op} = Number of evaluation operators
s_{op} = Number of synthesis operators

r_{op} = Number of representation mapping operators

The complexity measure for solvability of a project:

$$Cx_{Solvability} = \sum \left(k_1 \cdot a_{op} + k_2 \cdot s_{op} + k_3 \cdot e_{op} + k_4 \cdot r_{op} \right) \quad (2.29)$$

The complexity measure for degree of freedom of a problem:

$$Cx_{dof\_prob} = \left(\sum dof(idv) + \sum dof(ddv) + \sum dof(mg) - \sum dof(dr) \right) \quad (2.30)$$

The complexity of a design artifact based upon size:

$$Cx_{dof\_art} = \left(\sum dof(idv) + \sum dof(ddv) - \sum dof(dr) \right) \quad (2.31)$$

where

k_1, k_2, k_3 and k_4 are coefficient factors that account for the different reasoning complexities of the reasoning process, the domain knowledge that is available and required for each operator and the designer skill for executing that operator.

2.4. Summary

In this chapter, we reviewed some of the current and past discussions on engineering systems flexibility, with particular focus on manufacturing systems and network-based systems. A review of the existing definitions and measures of flexibility for engineering systems shows a multitude of perspectives on the subject at different levels and scales. Yet, in most cases, the measures of flexibility take into consideration a combination of probabilistic change, time impact of change, costs, benefits, and the designed or inherent response to change in the system. The study of the literature of systems engineering and manufacturing enables us in later Chapters of this thesis to recognize and extract the essential elements of flexibility. These elements of flexibility will be used to construct a framework to measure flexibility in space systems in Chapter 5.

In the next chapter, we will focus on the current and past discussions on flexibility in space systems, the main focus of this dissertation.

References:

(Beach 1998)

Beach, R.; Muhlemann, A.P.; Price, D.H.R.; Paterson, A.; Sharp, J.A. “Review of manufacturing flexibility,” European Journal of Operational Research, v 122, n 1, Apr, 2000, p 41-57

(Benjafaar 1992)

Benjaafar, S., Talavage, J.J., “Axiomatic measures of flexibility in advanced manufacturing systems,” 1992 IEEE International Conference on Systems, Man and Cybernetics, 1992, p 1379-83 vol.

(Benjafaar 1994)

Benjaafar, S., “Models for performance evaluation of flexibility in manufacturing systems,” International Journal of Production Research, 1994, Vol.32, No.6, 1383-1402.

(Beskese 2004)

Beskese, Ahmet, Kahraman, Cengiz; Irani, Zahir. “Quantification of flexibility in advanced manufacturing systems using fuzzy concept,” International Journal of Production Economics, v 89, n 1, May 8, 2004, p 45-56

(Bonchev and Buck 2000)

Bonchev, D., Buck, G. A., “Quantitative Measures of Network Complexity,” In: Complexity in Chemistry, Biology and Topology, D. Bonchev and D. H. Rouvray, Eds., KLUWER Academic, New York.

(Bonchev 2000)

Bonchev, D., “Overall Connectivities /Topological Complexities: A New Powerful Tool for QSPR/QSAR,” J. Chem. Inf. Comput. Sci. 40, 934-941, 2000.

(Bonchev 2003)

Bonchev, D., “On the Complexity of Directed Biological Networks,” SAR QSAR Envir. Sci., 14, 199-214, 2003.

(Brill 1989)

Brill, P.H., Mandelbaum, M., “On measures of flexibility in manufacturing systems,” International Journal of Production Research, 27 (5), 747±756, 1989.

(Browne et al. 1984)

Browne, J. Dubois, D., Rathmill, K., Sethi, S. P., and Stecke, K. E., 1984, “Classification of flexible manufacturing systems,” The FMS Magazine, 2 (2), 114± 117.

(Chen and Chung 1996)
Chen, I. J., and Chung, C.-H., 1996, "An examination of flexibility measurements and performance of flexible manufacturing systems," International Journal of Production Research, 34 (2), 379± 394.

(Choi 1998)
Choi, Sung-Ho; Kim, Ji-Soo. "Study on the measurement of comprehensive flexibility in manufacturing systems," Computers & Industrial Engineering, v 34, n 1, Jan, 1998, p 103-118.

(Correa 1994)
Correa, H. L., 1994, "Linking Flexibility, Uncertainty and Variability in Manufacturing Systems," (London: Avebury).

(de groote 1994)
De Groote, X., "The flexibility of production processes: a general framework," Management Science, v 40, n 7, July 1994, p 933-45.

(de Toni and Tonchia 1998)
De Toni, A., Tonchia, S. "Manufacturing flexibility: a literature review," International Journal of Production Research, v 36, n 6, June 1998, p 1587-617.

(El-Haik and Yang 1999)
El-Haik, B., Yang, K., 1999, "The components of complexity in Engineering design," IIE Transactions, 31, pp.925-34.

(Gerwin 1993)
Gerwin, D., 1993, "Manufacturing flexibility: a strategic perspective," Management Science, 39 (4), 395± 410.

(Gupta 1992)
Gupta, Y.P., Goyal, S., "Flexibility trade-offs in a random flexible manufacturing system: a simulation study," International Journal of Production Research, v 30, n 3, March 1992, p 527-57.

(Gupta 1993)
Gupta, D., "On measurement and valuation of manufacturing flexibility," International Journal of Production Research, v 31, n 12, Dec. 1993, p 2947-58.

(Harary 1995)
Harary, F., "Graph Theory," 5th Edition, Addison-Wesley, Reading, MA, 1995.

(Kahyaoglu 2002)
Kahyaoglu, Y., Kayaligil, S., "Conceptualizing manufacturing flexibility: an operational approach and a comparative evaluation," International Journal of Production Research, v 40, n 10, 10 July 2002, p 2187-206.

(Kochikar 1992)

Kochikar, V.P., Narendran, T.T, “A framework for assessing the flexibility of manufacturing systems,” International Journal of Production Research, v 30, n 12, Dec. 1992, p 2873-95.

(Kumar 1987)

Kumar, V., “Entropic measures of manufacturing flexibility,” International Journal of Production Research, v 25, n 7, July 1987, p 957-66.

(Lloyd 2003)

Lloyd, S., “Complex Systems: A Review,” ESD-WP-2003-01.16- ESD Internal Symposium.

(Magee and de Weck, 2003)

Magee, C.L., deWeck, O.L., “An Attempt at Complex System Classification,” ESD-WP-2003-01.02-ESD Internal Symposium.

(Martin 2004)

Martin, P. J., “A Framework for Quantifying Complexity and Understanding its Sources: Application to two Large-Scale Systems,” MIT ESD S.M thesis, 2004.

(Moses 2003)

Moses, J., “The Anatomy of Large Scale Systems,” ESD Internal Symposium, ESD-WP-2003-01.25.

(Moses 2004)

Moses, J., “Foundational Issues in Engineering Systems: A framing Paper,” Engineering systems monograph, march 2004.

(Nelson 1997)

Nelson, K.M., Nelson, H.J., Ghods, M., “Technology flexibility: conceptualization, validation, and measurement,” Proceedings of the Thirtieth Hawaii International Conference on System Sciences (Cat. No.97TB100234), 1997, pt. 3, p 76-87 vol.3.

(Parker 1999)

Parker, R.P., Wirth, A., “Manufacturing flexibility: measures and relationships,” European Journal of Operational Research, v 118, n 3, 1 Nov. 1999, p 429-49.

(Sethi and Sethi 1990)

Sethi, A. K., and Sethi, S. P., 1990, “Flexibility in manufacturing: a survey,” International Journal of Flexible Manufacturing Systems, 2 (4), 289± 328.

(Shannon and Weaver 1949)

Shannon, C., Weaver, W., “Mathematical Theory of Communications,” University of Illinois Press, Urbana, IL, 1949.

(Shewchuk 1998)

Shewchuk, J.P., Moodie, C.L., “Definition and classification of manufacturing flexibility types and measures,” International Journal of Flexible Manufacturing Systems, v 10, n 4, Oct. 1998, p 325-49.

(Shewchuk 1999)

Shewchuk, J.P., “A set of generic flexibility measures for manufacturing applications,” International Journal of Production Research, v 37, n 13, 10 Sept. 1999, p 3017-42.

(Shewchuk 2000)

Shewchuk, J.P., Moodie, C.L., “Flexibility and manufacturing system design: an experimental investigation,” International Journal of Production Research, v 38, n 8, 20 May 2000, p 1801-22.

(Slack 1987)

Slack, N., 1987, “The flexibility of manufacturing systems,” International Journal of Operations & Production Management, 7 (4), 35± 45.

(Suarez 1995)

Suarez, F.F., Cusumano, M.A., Fine, C.H., “An empirical study of flexibility in manufacturing,” Sloan Management Review, v 37, n 1, Fall 1995, p 25-32.

(Summers and Shah 2003)

Joshua D. Summers and Jami J. Shah, “Developing Measures of Complexity for Engineering Design,” ASME 2003 Design Engineering Technical Conferences and Computer and Information in Engineering Conference, Chicago, 2003.

(Suh, 1999)

Suh, N., 1999, “A theory of complexity, periodicity and the design axioms,” Research in Engineering design, 11, pp 116-31.

(Sussman 2000)

Sussman, J. M., “Ideas on Complexity in the System: Twenty Views,” ESD-WP-2000-02.

(Upton 1995)

Upton, D. M., 1995a, “Flexibility as process probability: the management of plant capabilities for quick response manufacturing,” Journal of Operations Management, 12 (3± 4), 205±224.

(Watson and McCabe 1996)

Watson, A. H., McCabe, T., J., "Structured Testing: A Testing Methodology Using the Cyclomatic Complexity Metric." (Online NIST Article) http://hissa.ncsl.nist.gov/HHRFdata/Artifacts/ITLdoc/235/mccabe.html (1996).

(Whitney, 2000)

Whitney, Daniel E. (MIT). “Research issues in manufacturing flexibility - an invited review paper for ICRA 2000 symposium on flexibility,” Proceedings - IEEE International Conference on Robotics and Automation, v 1, 2000, p 383-388.

(Zahran 1990)

Zahran, Ismail M.; Elmaghraby, Adel S.; Shalaby, Mohammed Adel. “Evaluation of flexibility in manufacturing systems,” Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, Nov, 1990, p 49-52.

(Zelenovich 1982)

Zelenovich, D. M., 1982, “Flexibility: a condition for effective production systems,” International Journal of Production Research, 20 (3), 319± 337.

(Zhang 2003)

Zhang, Q., Vonderembse, M.A., Lim, J., “Manufacturing flexibility: defining and analyzing relationships among competence, capability, and customer satisfaction,” Journal of Operations Management, v 21, n 2, March 2003, p 173-91.

Chapter 3

"There is nothing wrong with change, if it is in the right direction"
-- *Winston Churchill*

3. Space Systems Flexibility: A Literature Review

THE concept of flexibility has gained extensive attention within the context of space systems in recent years. There have been efforts in the direction of defining and clarifying the concept of flexibility in space systems, as well as measuring its value, to the extent possible. In this chapter, we will look at the state of the art in the field of space systems flexibility and discuss the merits and shortcomings.

3.1. Flexibility on the Basis of Cost per Function

One of the first efforts to quantify flexibility in space systems started with Shaw (1999). In his doctoral thesis, he presents a communication satellite system as an information network. A satellite is decomposed into its most important functional modules. The functional modules are the elements that impact the transfer of information from source to sink. Next, four quality-of-service parameters are defined which relate the quantity, quality, and availability of information. These four are signal isolation, information rate, information integrity, and information availability.

3.1.1. Shaw's Metric for Flexibility in Telecommunication Satellites

Shaw integrates the financial and market view of a satellite system with its technical design and specification. He introduces Cost per Function (CPF) for the satellites, which is a measure of the average cost incurred to provide a satisfactory level of service to a single Origin-Destination pair within a defined market.

$$CPF = \frac{lifetime\_cost}{\#of\_satisfied\_users} \tag{3.1}$$

Then he introduces adaptability metrics as "how flexible a system is to changes in the requirements, component technologies, operational procedures or even the design mission" (Shaw 1999). He defines two types of adaptability as follows:

Type 1 adaptability assesses the sensitivity of the capability, cost, and performance of a given architecture to realistic changes in the system requirements or component technologies. The mathematical form of this measure also makes it entirely compatible with conventional economic analyses of commercial ventures and adds enormous utility to the metric for investment decision-making and business planning. The adaptability metric represents the elasticity[7] of the CPF metric with respect to changes in the requirements or the component technologies. This definition of flexibility is an adaptation of the concept of elasticity in the context of microeconomics.

Type 1 adaptability metrics are defined as the percentage change in CPF to a one percent change in "relevant variable." In his definition, the relevant variables can be Isolation, Rate, Integrity, and Availability. The metrics are as follows:

$$E_{Is} = \frac{\Delta CPF / CPF}{\Delta I_s / I_s} \tag{3.2}$$

---

[7] Elasticity is defined as the percentage change that will occur in one variable in response to a one percent change in another variable. It can be written as:

$$E_p = \frac{\Delta Q / Q}{\Delta P / P} = \frac{(P_1 + P_2) \cdot \Delta Q}{(Q_1 + Q_2) \cdot \Delta P}$$

where Q is the quantity of demand and P is the price.

$$E_R = \frac{\Delta CPF / CPF}{\Delta R / R} \tag{3.3}$$

$$E_I = \frac{\Delta CPF / CPF}{\Delta I / I} \tag{3.4}$$

$$E_{Av} = \frac{\Delta CPF / CPF}{\Delta Av / Av} \tag{3.5}$$

where E_{Is}, E_R, E_I , E_{Av} are the Isolation, Rate, Integrity, and Availability elasticities of the CPF, with respect to the system requirements Is, R, I, and Av. In the same fashion, the elasticity of change in different technologies can be calculated. Figure 3.1 shows a schematic of CPF as a function of *x*.

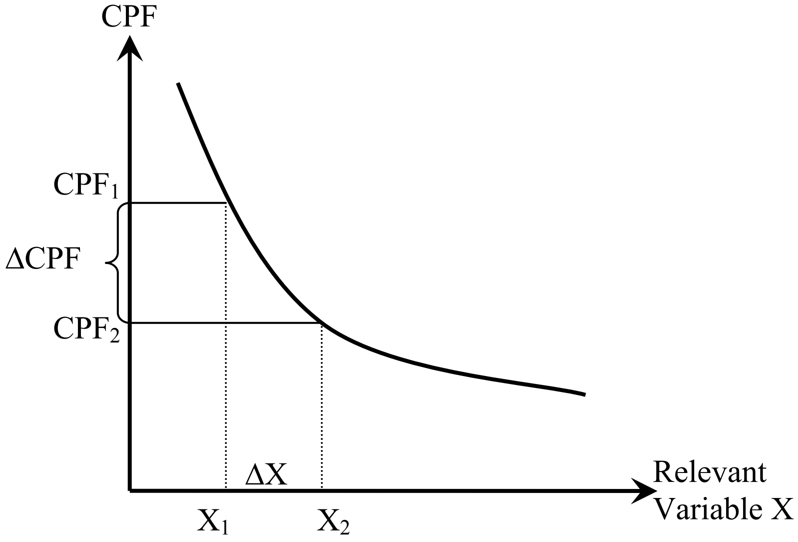


Figure 3.1. A schematic of cost per function as a function of *x*

Type 2 adaptability measures the flexibility of an architecture for performing a different mission, or at least an augmented mission set. The metric is defined on the basis of the fact that a change in the design mission represents a change in the market and all the system requirements. Flexibility *F* is defined to be the proportional change in the *CPF* in response to a particular mission modification. The measure is defined as

$$F\big|_X = \left.\frac{\Delta CPF}{CPF}\right|_X \qquad (3.6)$$

where X is just an identifier to specify the mission modification. This metric is used for comparing competing designs since it measures the sensitivity of the CPF to mission modifications. Shaw uses this flexibility metric to decide between alternate architectures during the conceptual design phase of a program, especially if the mission is likely to change over the lifetime.

3.1.2. Analysis of Shaw's metric

The adaptability metric type 1 measures the sensitivity of two variables of the system to each other. In this definition, the changes in the cost per function are compared to the changes of the variable of interest. This metric is able to measure change in the system, but only one variable at a time. If a variable of interest changes with respect to CPF in such a way that it shows increased flexibility, it might show decreased flexibility with respect to some other important variable of the system. Thus, it cannot capture the total change in the system in one step (it is not a multifunctional measure).

3.2. Black-Scholes Approach to Flexibility in Space Systems

In his thesis "Weaving Time into System Architecture," Saleh (2002) focuses on issues of flexibility in system design and spacecraft design lifetime, as well as on-orbit servicing as a way to provide flexibility in space systems.

3.2.1. Saleh and Lamassoure flexibility metric for Space Systems

One major fundamental contribution of Saleh's work is introducing temporal considerations into system architecture. Traditionally, system architecture has been viewed as a snapshot approach to the system. The temporal approach considers the flow of service or utility that the system will provide over its lifetime. Saleh discusses the relationship of time, uncertainty, and flexibility in the system. The systems that thrive longer are the ones that are capable of coping with unpredictability and change in their environments.

Saleh defines the *flexibility* of a design as the property of a system that allows it to respond, in a timely and cost effective way, to changes in its initial objectives and requirements--both in terms of capabilities and attributes—that occur after the system has been fielded (Saleh 2002). He also defines *robustness* as the property of a system which allows it to continue satisfying a fixed set of requirements, in the environment or within the system itself, despite changes occurring after the system has entered service from the nominal or expected environment or system design parameters.

Next, he builds a case for flexibility in high-value on-orbit assets. Due to the high value of on-orbit assets, it is desirable to build space systems that can adapt to new or emergent missions and roles instead of being replaced with a new one. Saleh believes that flexibility reduces a design's exposure to uncertainty and provides a solution for mitigating market risks as well as risks associated with technology obsolescence. Requirement changes are also mentioned as a main driver for flexibility.

As an initial step towards valuating flexibility, Saleh introduces a formula to express expected present value of a system as a function of its design lifetime. This formula is based on the market and financial view of a space system and involves market analysis and operation, engineering, and cost analysis. The relationship is presented as follows:

$$V(T_{Life}) = \int_{0}^{T_{Life}} [u(t) - \theta(t)] \times e^{-rt} dt - C(T_{Life}) \tag{3.7}$$

where

$V(T_{Life})$: Expected present value of a system architecture as a function of its design lifetime

$u(t)$: Utility rate of the system

$\theta(t)$: Cost of operating the system per day

$C(T_{Life})$: System cost profile as a function of its design lifetime

r: Discount rate

In the next step, Saleh recognizes the relationship between $u(t)$ and market volatility. Now uncertainty is implemented into the formula through the volatility σ. Two major assumptions are embedded in this study. First, the value of the market the system is serving has a lognormal probability density function. This is based on the real option theory that the future value of a real asset behaves as a financial stock and, therefore, volatility can be assigned to it. Second, he assumes the revenues generated per day by the system are directly correlated with the dynamics of the market.

In the next step, a framework is developed to capture the value of flexibility provided by on-orbit servicing. Several options, such as servicing and upgrading, are made available to the space missions through on-orbit servicing. If a servicing infrastructure is available on-orbit, these options can be exercised after the spacecraft has been deployed. Saleh proposes a new perspective on the issue by analyzing the problem from the customer's perspective instead of the usual provider's perspective.

The value of flexibility in on-orbit servicing from a customer's perspective can be calculated through decision tree analysis (DTA) and real options theory, with a particular emphasis on the Black-Scholes formula (Saleh 2003). The values calculated are independent of servicing structure, and the value of servicing is separated from its cost. Through this calculation, we can measure the maximum cost cap below which servicing makes economic sense.

For valuating flexibility through decision tree analysis (DTA), the following formula is suggested:

$$V_{flx} = V_{DTA} - NPV \qquad (3.8)$$

where V_{DTA} is the value of DTA with options in place, and NPV is the traditional net present value calculation. Saleh's second suggested way of valuating flexibility is through the Black-Scholes formula, which is being modified to be used in case of on-orbit servicing (Lamassoure et al. 2002). The formulation is as follows:

$$V_{DTA} = S_0 \times N(d_1) - e^{-rT_0} \times (E + C_{ops}) \times N(d_2) \qquad (3.9)$$

where

$$N(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-t^2} dt$$

$$d_1 = \frac{\left[\ln\left(\frac{S_0}{E}\right) + \left(\alpha + \sigma^2/2\right) T_0 \right]}{\sigma\sqrt{T_0}}$$

$$d_2 = d_1 - \sigma\sqrt{T_0}$$

The Black-Scholes formula is suggested for capturing the value of flexibility because instead of a limited number of branches of chance and nodes, an infinite number of branches shoots out of the event node. The assumption is that the revenues are continuous over time.

3.2.2. Limitations of Black-Scholes approach to flexibility

The Black-Scholes formula is part of the large field of real options theory. The foundational papers were published in 1973 by Black and Scholes, and concurrently by Merton. This work had a large impact on development of huge markets for financial options, and specifically, options "on"[8] products. The Black-Scholes option pricing formula, for which they won the Nobel Prize in 1997, is as follows:

$$C = S \cdot N(d_1) - \left(K \cdot e^{-rt} \cdot N(d_2)\right) \qquad (3.10)$$

where

$$d_1 = \frac{\left[\ln\left(\frac{S}{K}\right) + \left(r + \sigma^2/2\right) \cdot t \right]}{\sigma\sqrt{t}}$$

$$d_2 = d_1 - \sigma\sqrt{t}$$

C : Option value

S : Current price of asset

---

[8] Real options "on" projects are financial options, but they are on technical things and they treat technology as a black box.

K : Strike price of the asset

$N(x)$: Cumulative probability distribution function up to x of normal distribution with average zero and standard deviation equal to one

σ : Standard deviation of returns on asset

r : Risk-free rate of interest

t : Time to expiration

The formula is used in a *very special situation* (de Neufville 2004). This option is a *European call*[9] option on a *non-dividend paying asset.* That means it is only usable on a specific date and the asset does not change over the option period.

This formula is a solution to the "Stochastic Differential Equation" (SDE) that defines the movement of the option value over time. The boundary conditions for solving the SDE are

- It is a call
- Only one exercise time exists
- The asset yields no intermediate benefit

Hence, when using Black-Scholes formula, the following assumptions exist (de Neufville 04):

- Price assumption: according to de Neufville (2004), the Black-Scholes approach is valid when a system produces a commodity that has quoted prices set by the world market. It might still be valid for the goods that lead to revenues. The approach does not work for systems that deliver services that are not marketable, such as national defense.
- Replicating portfolio assumption: The Black-Scholes formula is based on the assumption that it is possible to set up a replicating portfolio for the asset. Then the approach works when the product is a commodity. It might still be valid even if a market is non-existent, if a reasonable approximation can still be constructed.
- Volatility assumption: Black-Scholes formula is valid when there is an established market with a long history of trades that generates good statistics. The approach is

---

[9] A European option is only usable on a specific date, while an American option is usable any time in the period.

questionable when no market is observable or assets are unique. The approach is not valid for the case of *new technologies* or *enterprises with no data.*

- Duration assumption: The Black-Scholes approach assumes the volatility of the asset price is stable over the duration of the option. This is true for short-term options (3 months or a year) in a stable industry or activity. It is questionable for industries that are in transition, such as communications. The approach is not true for long duration projects that major changes in the states of market, regulations, or technologies are highly uncertain.

With all the assumptions embedded in the Black-Scholes formula, it is unsuitable and in most cases invalid for space systems that pay dividends, use new technologies, do not have an established market, or have a long duration and uncertain state of market, regulations, or technologies. In such cases, the other methods of valuating flexibility in real option theory, such as Decision Tree Analysis, can be used. However, under special circumstances, Saleh's formula can be used for measuring the value of flexibility in on-orbit servicing

3.3. Provider-side Flexibility in On-orbit Servicing

Nilchiani (2002) proposed an orbital transportation network analysis (OTNA) methodology for on-orbit refueling of satellites. The methodology allowed identification of suitable system architectures for strategic planning, in addition to providing insight into possible bottlenecks for tactical planning of everyday operations. A system dynamics modeling approach was used to implement OTNA, providing useful insight into the sensitivities of different system parameters in a non-linear complex interaction. The methodology can be easily used to identify impacts of system architecture, deployment strategy, schedule slip, market demographics, and risk on system performance, cost, and flexibility. OTNA will also allow a more detailed design, which can be robust in case of changing demand volume, an expanding network, changing functionality, and service type variations. The model can be adapted to include on-orbit servicing and tugging operations as well.

The Orbital Transportation Network consists of the following components:

- *Target units*, which are destination points in our defined network. They include military, commercial, and scientific satellites.
- *Infrastructures* which are origin points in the network. They include fuel Depots, space station, service/repair stations, and ground stations.
- *Vehicles* transfer material in the network. They include Shuttles, launch vehicles (Earth to Orbit) and Orbital Maneuvering Vehicles (OMVs).

Two metrics were chosen to represent the operation of the system under different architectures and external parameters from the provider's perspective. These are the value metric and the performance metric. The performance metric is defined as the product of availability of service and reliability of service, and measures from 0 to 1.0. The value metric is defined as the ratio of the price a customer is ready to pay for the refueling of a satellite (a fraction of the value of continued operation of the satellite), $Pr_{customer,}$ to the cost of the refueling service to the provider $C_{provider}$. Value metrics higher than 1.0 indicate that the provider will be able to make a profit from offering the service. Initial analysis shows that refueling using an orbital transportation network can be achieved at prices lower than the market value for the service.

Research by Nilchiani and Hastings (2003) builds on the Orbital Transportation Network Analysis methodology proposed in earlier research. They reviewed the literature of flexibility, the different types of flexibility that can apply to an orbital transportation network, and their relationships to the system architecture. The focus is on provider-side flexibility for space systems. This research adapts and expands on manufacturing flexibility concepts to define provider-side flexibility metrics for space systems.

A provider-side flexibility metric is defined as a combination of the different types of flexibilities. Service flexibility for an orbital transportation network can be defined as the combination of three types of flexibilities, which play out in different time frames: mix flexibility (long-term), volume flexibility (mid-term), and emergency service flexibility (short term). Using these definitions, different architectures for an orbital transportation network were evaluated on the basis of their flexibility, value, and performance metrics.

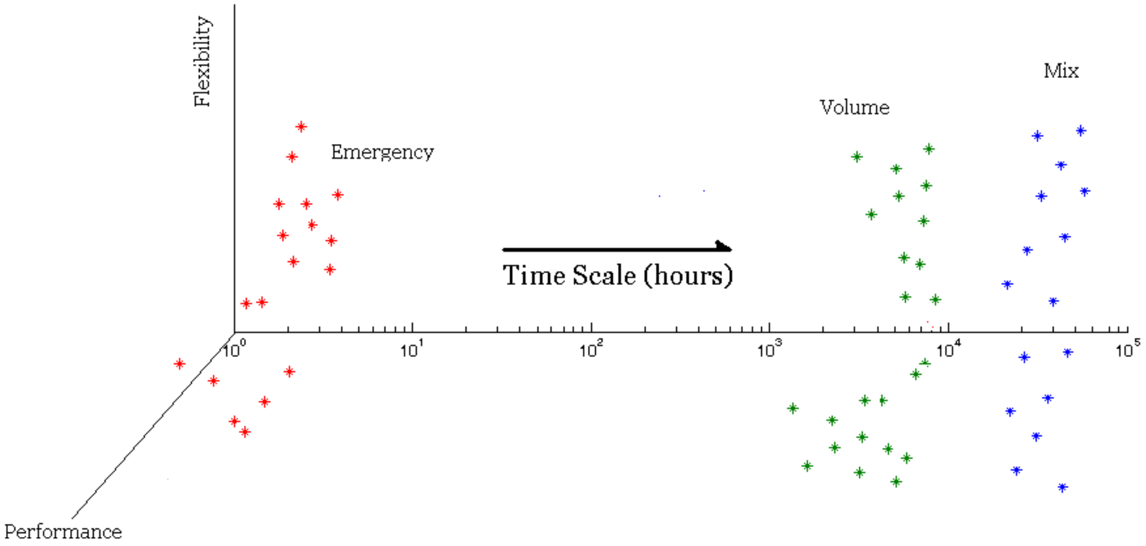


Figure 3.2. Service flexibility components and their respective time scales.

Mix flexibility is defined as the strategic ability to offer a variety of services with the given system architecture. In the context of the orbital transportation network, the types of services that can be provided by the system include: on-orbit refueling, servicing, upgrading, and tugging of satellites, as well as less crucial services such as housing scientific instrumentation within the existing infrastructure. In this research, the mix flexibility metric is defined as the ratio of the profit resulting from adding more service types (taking into account additional costs incurred by the necessary changes in architecture) to the profit with a single service only. Mix flexibilities larger than 1.0 indicate a system that increases in value by offering multiple service types. For this purpose, mix flexibility is defined by Equation 3.11,

$$f_m = \frac{S_m - E_m}{S - E} \quad , \qquad (3.11)$$

where f_m is the mix flexibility, E is the total system cost over the lifetime of orbital transportation network operations, and S is the total revenue over the lifetime of the system. The subscript m denotes the case where multiple types of services (refueling, servicing, tugging, etc.) are offered.

Volume flexibility is defined as the ability to respond to drastic changes in demand. In the orbital transportation network system, the volume flexibility metric is defined as the value of the service for the provider over the range of market uncertainties, determined by a Black-Scholes approach as proposed by Saleh et al. (2002), divided by the traditional NPV of the service for the provider at currently projected demand. Values equal to or larger than 1.0 indicate that the expected value of the system over the range of market uncertainties is higher than its value at currently projected demand, indicating system flexibility with regard to demand change. Thus,

$$f_v = \frac{\int_0^E e^{-rt_m}(S-E)p(S)dS}{NPV}, \qquad (3.12)$$

where f_v is the volume flexibility. The maturation time t_m is defined as the time period, the infrastructure investment, after which the system begins to operate with a mature client base. E is the total system cost over the lifetime of the system and S is the total system revenue in the period between the maturation time and the operation lifetime of the system. *NPV* represents the risk-free investment return and *p(S)* represents the log-normal distribution of system revenues over the range of client-base uncertainties. The numerator represents the total profit generated in the system given a probability density function corresponding to different client bases, ranging from no clients at all to the maximum number of clients the system can support. The denominator represents the return on investment if the initial infrastructure investment were invested in risk-free bonds. For ratios larger than one, investments in the orbital transportation infrastructure under all operating conditions would be more profitable than the risk-free investment.

Emergency service flexibility is defined as the tactical ability of the system to provide emergency (non-scheduled) services to satellites in duress. The emergency flexibility metric can be defined as the excess annual servicing capacity of the system (maximum service capacity) divided by the current level of service per year. Values larger than one show the fractional increase of additional emergency services that the system can respond to without lowering performance on its scheduled services.

$$f_E = \frac{Cap_{\max}}{Cap_{current}} \tag{3.13}$$

Service flexibility is then obtained by taking the weighted average of the above flexibilities. This ensures that the flexibility preferences of the provider are taken into consideration. The weight coefficients are determined by the provider, based on the priorities specified in the orbital transportation network mission objectives. For instance, for a client base consisting mostly of commercial satellites, volume flexibility and mix flexibility have a greater weight than emergency flexibility, whereas for military satellites, emergency flexibility and mix flexibility have higher weight coefficients than volume flexibility. Different metrics are explored for objectives with different weights, and all possible architectures are ranked in a trade-space, based on the resulting flexibility, value, and performance metrics. Service flexibility can thus be defined as:

$$f = \frac{\sum_{i=M,V,E} w_i f_i}{\sum_{i=M,V,E} w_i}, \tag{4}$$

where w_i denotes the user-defined weight for the different flexibilities defined above.

The use of these metrics was, however, often limited to the case of on-orbit servicing. The above-mentioned metrics should be modified for application to other space systems.

3.4. Customer-side Flexibility

In the context of on-orbit servicing of the Hubble Space Telescope, Joppin (2003) investigates the value of customer-side flexibility with regard to cases of satellite upgrade with a focus on commercial missions of GEO satellites. She chooses a real option theory approach to account for flexibility gained through on-orbit servicing and examines the volatility of the market and also the effect of upgrading on the revenue. The upgrade is to the solar panel of the satellite and the three options of replacing, servicing, and abandoning the mission are considered.

Joppin (2004) investigates the case of upgrade and repair of a scientific mission. She develops a model of a serviceable scientific mission based on the Hubble space telescope. In this study, the utility of the mission, measured in discovery efficiency, is used instead of a monetary evaluation of the mission. A simulation is used to model uncertainty of new technologies, spacecraft failure, and catastrophic failure, of the servicing mission. The value of the option to repair and service a spacecraft are investigated through the data gathered in manned servicing missions. In order to valuate the option, a base case architecture has been chosen. The base case is defined as a satellite that cannot be serviced. Three options of satellite repair, instrument upgrade, and bus upgrade on a serviceable satellite have been investigated.

The utility of the on board spacecraft instrument is presented through the discovery efficiency. This utility often used to describe and compare the capacity of observation cameras, and is defined as the product of the field of view and the throughput of the instrument. Finally as a result, the cost of the option, range of utility and the range of probability of each option are presented.

McVey (2002) proposes a valuation framework for measuring on-orbit servicing flexibility. Her proposed framework can be seen in Figure 3.3. She uses real options theory with a special focus on using the Black-Scholes formula, which has been proposed for use in on-orbit servicing by Saleh (2002). McVey creates a baseline case of a GEO satellite and 12 different alternatives and scenarios to compare to the baseline case. The value of flexibility for each alternative is being calculated through the Black-Scholes formula and added to the value of baseline case.

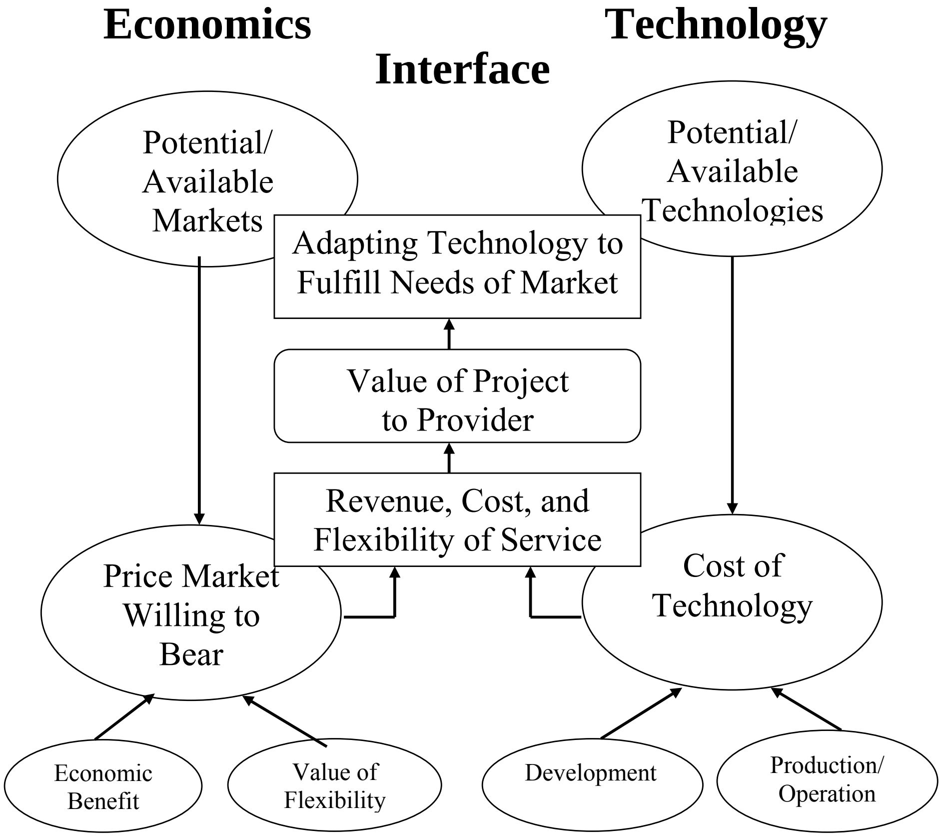


Figure 3.3. A suggested framework for capturing the value of flexibility in on-orbit servicing (from McVey 2002)

3.5. Real Option Approach "in" Space Systems

In another approach to design flexibility in space systems, De Weck et al. take a real option approach "in"[10] the space systems. The case of Low Earth Orbit constellation of communication satellite as a system with high uncertainty in demand is studied. The high uncertainty in the number of users and their activity level are the major drivers that might lead the system to economic failure. An alternative approach is suggested in order to create flexibility in the system. The main idea is to deploy the constellation of satellites progressively, starting with smaller and more affordable capacity which can be expanded to a larger constellation of satellites by launching new satellites and reconfiguring the old ones. This approach enables the designers and the managers of the system to match the system evolution path to the actual unfolding demand scenario. The lifecycle costs of the

---

[10] Real option approach in the systems is defined as designing flexibility in the technological system. This usually needs a comprehensive technical knowledge of the engineering of the system.

flexible architectures are calculated through a binomial tree for demand modeling and subtracted from a traditional base case architecture. The value of flexibility is defined here as the discounted money saved compared to the traditional approach. The difference between the lifecycle cost of the traditional architecture and the average lifecycle cost of the optimal path of expansion thus creates the value of the flexibility. Finally, a generalized framework is proposed for large-capacity systems facing high demand uncertainty.

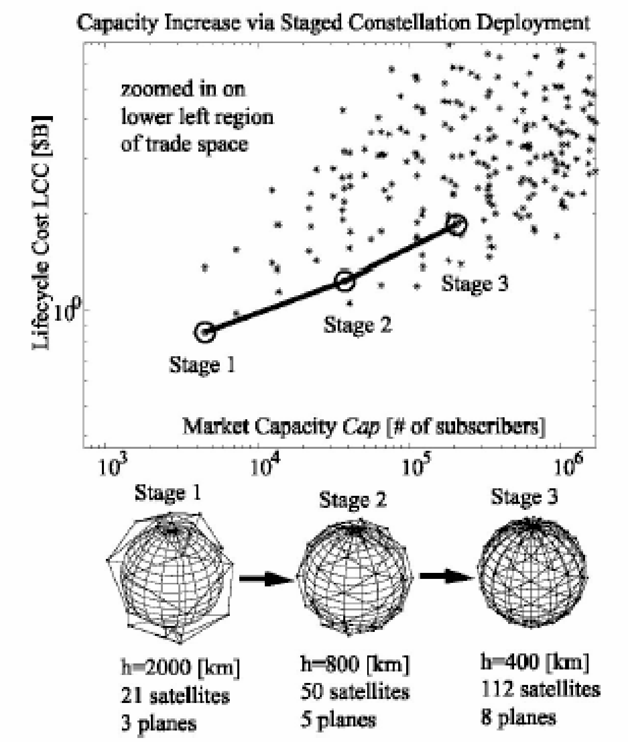


Figure 3.4. Staged deployment path at the low capacity end of the trade space (from de Weck et al. 2004)

3.6. Summary

In this chapter, we reviewed the state of the art in the literature on space systems flexibility. The field is relatively unexplored, and most flexibility definitions and metrics proposed pertain to particular aspects of space systems and cannot be expanded to other systems. Additionally, many of the assumptions underlying some of the metrics make their field of application very narrow.

This concludes the literature review of this dissertation. In the next chapter, we will look at common elements of flexibility in space systems, and develop an understanding of flexibility based on its fundamental concepts.

References:

(de Weck et. al. 2003)

Olivier L. De Weck; Richard De Neufville; Mathieu Chaize. “Staged Deployment of Communications Satellite Constellations in Low Earth Orbit,” Journal of Aerospace Computing, Information, and Communication 2004, 1542-9423 vol.1 no.3 (119-136).

(Hastings and Nilchiani 2002)

D. Hastings and R. Nilchiani. “Developing an orbital transportation network analysis methodology for on-orbit refueling of satellites,” AIAA CoreTech 2002 Conference Proceedings.

(Joppin 2003)

D. Hastings and C. Joppin. “Evaluation of the Value of the Flexibility Offered by On-orbit Servicing: Case of Satellite Upgrade,” AIAA-2003-6366, AIAA Space 2003 Conference and Exposition, Long Beach, California, Sep. 23-25, 2003.

(Joppin 2004)

C. Joppin and D. Hastings. “Upgrade and Repair of a Scientific Mission Using On-Orbit Servicing Based on the Hubble Space Telescope Example,”AIAA-2004-6052, Space 2004 Conference and Exhibit, San Diego, California, Sep. 28-30, 2004.

(Lamassoure, 01)

Elisabeth S. Lamassoure. “A Framework to Account for Flexibility in Modeling the Value of On-orbit Servicing for Space Systems,” Master's thesis, MIT, Department of Aeronautics and Astronautics, May 2001.

(Lamassoure et al., 2002)

E. Lamassoure, J. H. Saleh, D. E. Hastings. “Space Systems Flexibility Provided by On-orbit Servicing: Part 2,” Journal of Spacecraft and Rockets, Vol. 39, No. 4, July–August 2002.

(McVey 2002)

Michelle E. McVey, “Valuation Techniques for Complex Space Systems: An Analysis of a Potential Satellite Servicing Market,” Thesis, 2002.

(Nilchiani and Hastings 2003)

R. Nilchiani and D. Hastings. “Measuring Flexibility in Design of an Orbital Transportation Network,”AIAA-2003-6367, AIAA Space 2003 Conference and Exposition, Long Beach, California, Sep. 23-25.

(Saleh 2002)

Joseph H. Saleh. “Weaving time into system architecture: new perspectives on flexibility, spacecraft design lifetime, and on-orbit servicing,” PhD thesis, MIT, Department of Aeronautics and Astronautics, 2002.

(Saleh et al. 2002)

J. H. Saleh, E. Lamassoure, D. E. Hastings. “Space Systems Flexibility Provided by On-orbit Servicing: Part 1,” Journal of Spacecraft and Rockets, Vol. 39, No. 4, July–August 2002.

(Saleh 2003)

Joseph H. Saleh; Elisabeth S. Lamassoure; Daniel E. Hastings; Dava J. Newman. “Flexibility and the Value of On-Orbit Servicing: New Customer-Centric Perspective,” Journal of Spacecraft and rockets 2003, 0022-4650 vol.40 no.2 (279-291).

(Shaw et. al. 1999)

G. B. Shaw, D. W. Miller, D. E. Hastings. “Development of the Quantitative Generalized Information Network Analysis (GINA) Methodology for Satellite Systems,” Journal of Spacecraft and Rockets, 2001,0022-4650 vol.38 no.2 (257-269).

(Shaw 1999)

Graeme B. Shaw. “The generalized information network analysis methodology for distributed satellite systems,” PhD thesis, MIT, Department of Aeronautics and Astronautics, 1999.

Chapter 4

> "It is change, continuing change, inevitable change that is the dominant factor in society today. No sensible decision can be made any longer without taking into account not only the world as it is, but the world as it will be."
>
> -- *Isaac Asimov*

4. Common Elements of Flexibility in Space Systems

IN the previous chapters we looked at flexibility from a variety of different standpoints. Sifting through the numerous definitions and metrics introduced in the literature, one can see common threads that run through the different ways the concept of flexibility has been approached within the field of space systems, but also extend to other engineering systems that are concerned with flexibility. In this chapter, we will attempt to extract and study these crucial elements of flexibility as a basis for constructing effective measures of flexibility that can be applied to a wide range of cases. This in effect is a systems approach to building up metrics for flexibility from its foundational elements, rather than to start from metrics that apply to a particular system of interest.

4.1. The Common Elements of Flexibility

We earlier defined flexibility as the ability of a system to adapt to uncertain internal or external changes affecting its value delivery, in a timely and cost-effective manner. In other words, flexibility is the *ease* with which changes in value delivery in a system can be addressed. Here *ease* refers to the cost-effectiveness of addressing change.

Integrating the definitions of flexibility presented in Chapters 2 and 3, the following elements are observed to be crucial in defining a measure for flexibility:

1. Boundary of the system to be studied
2. Aspects of system to which flexibility is applied
3. Time window in which flexibility is observed in the system
4. The uncertain and probabilistic nature of the future of the system
5. The degree of access to the system in order to apply the option or flexibility
6. Responses of the system to change through changes from the owner's, designer's, operator's, and user's perspective in the value delivery.

Schematics of elements of flexibility can be seen in Figure 4.1. These elements are discussed in detail in the following sections.

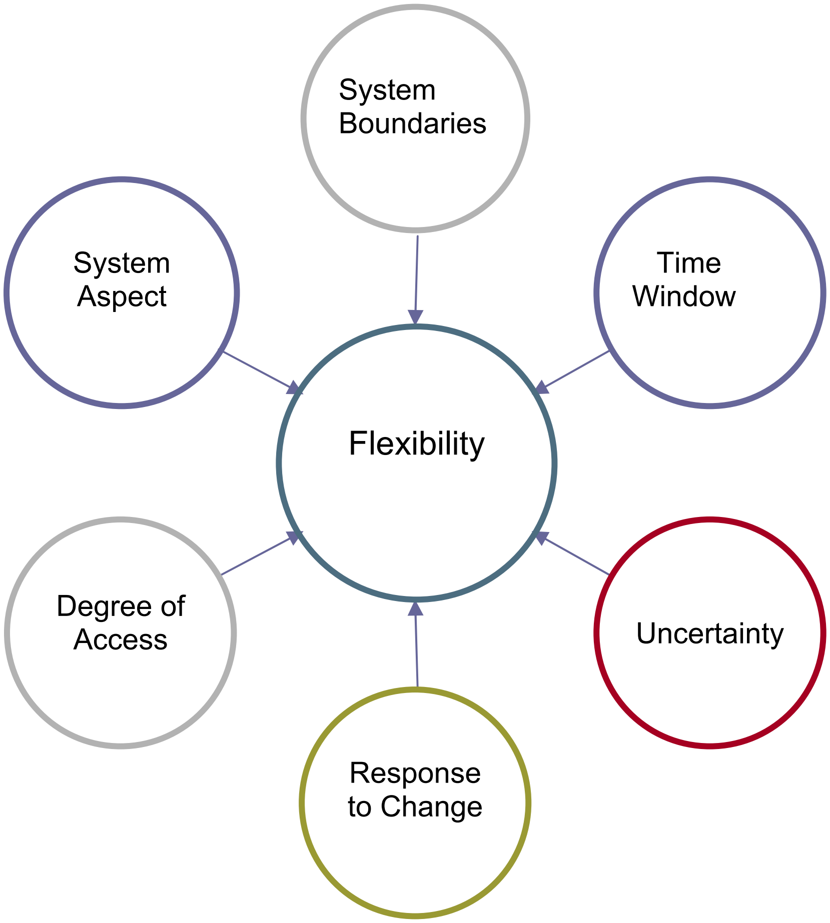


Figure 4.1. Crucial elements in building the concept of flexibility

4.2. System Boundary

The first step in accounting for flexibility in a system is to define and clarify the boundaries of the system to be studied. The boundaries of the system play an important role in defining, measuring, and implementing flexibility in a system. Boundaries may be physical, temporal, logical, or virtual.

Depending on the definition and the choice of boundary, different values of flexibility can be observed in a system. Figure 4.2 shows the different physical boundaries within which we can evaluate flexibility.

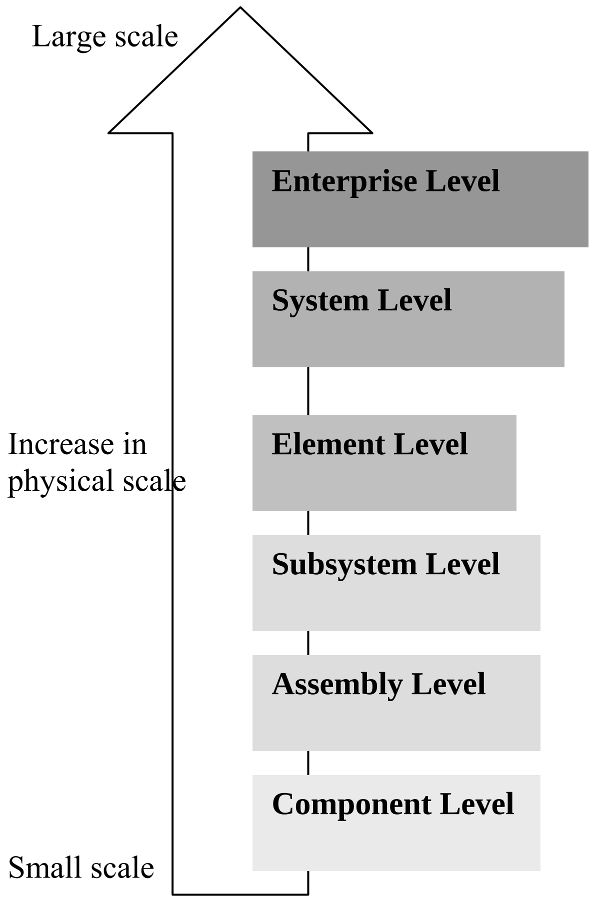


Figure 4.2 Different physical system boundaries for evaluation of systems flexibility

While a spacecraft may not show flexibility on a component level, it may be flexible on a subsystem or system level. In the following subsections, we will look at how boundaries can affect the "value" of flexibility.

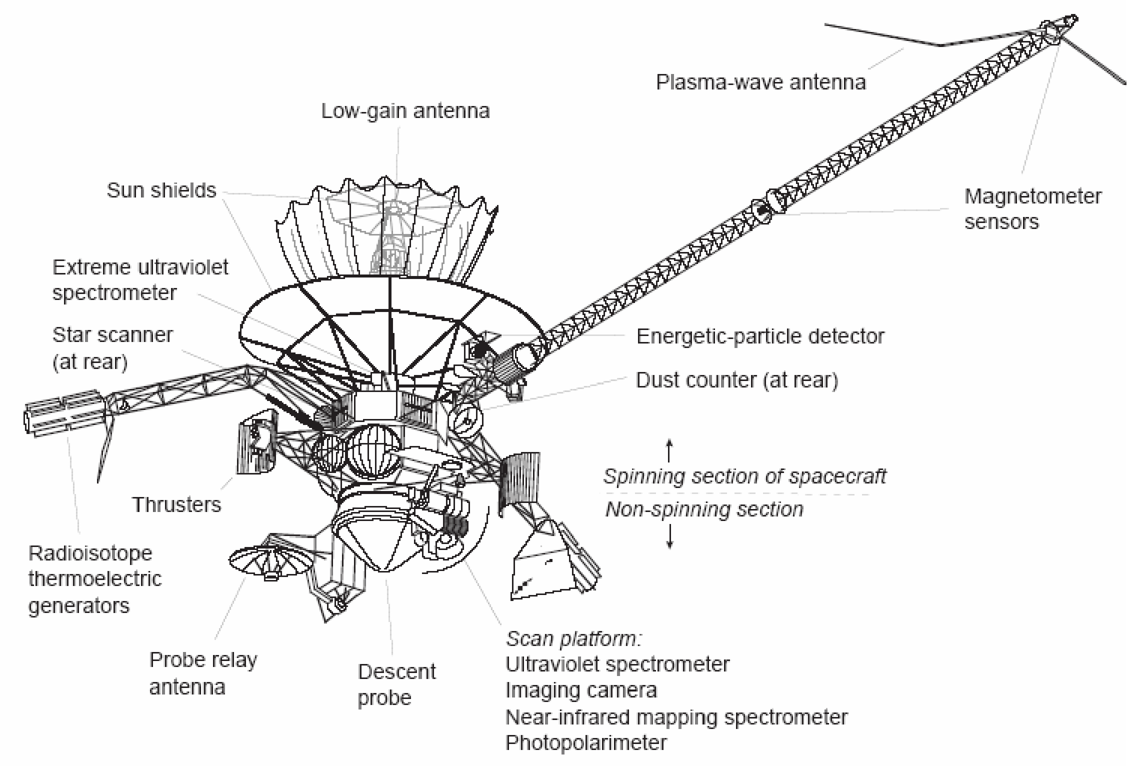


Figure 4.3 Galileo spacecraft (Source: NASA)

4.2.1. System Boundary Illustration: Galileo spacecraft

The Galileo spacecraft was launched in 1989. The Galileo mission had originally been designed for a direct flight of about 3.5 years to Jupiter. The spacecraft was scheduled to deploy its high-gain antenna in 1991 as it moved away from the Sun and the risk of overheating ended. The antenna, however, failed to deploy fully because a few of the antenna's 18 ribs were held by friction in the closed position. Despite exhaustive efforts to free the ribs, the antenna would not deploy. From 1993 to 1996, extensive new flight and ground software was developed, and ground stations of NASA's Deep Space Network were enhanced in order to perform the mission using the spacecraft's low-gain antennas. To offset some of the performance loss, the spacecraft's computer was extensively reprogrammed to include new data compression and coding algorithms. An innovative combination of new, specially developed software for Galileo's on-board computer and improvements to ground-based signal receiving hardware in the Deep Space Network enabled the spacecraft to accomplish at least 70 percent of its original mission science goals using only its small, low-gain antenna, despite the failure of its high-gain antenna (Marr 1994). Here the high-gain antenna had no flexibility, meaning there was no alternative way for it to be used once one deployment mechanism failed. Yet the spacecraft itself was flexible in addressing this change through a combined software design and hardware reallocation.

4.2.2. System Boundary Illustration: Distributed Satellite Systems (DSS)

A distributed satellite system (DSS) is defined as a system of multiple satellites designed to work together in a coordinated fashion to perform a mission. Some examples of DSS are the Global Positioning System for navigation, low-Earth-orbit global mobile communications constellations, and proposed separated spacecraft interferometers for astronomy (Shaw et al. 2000). While each of the individual satellites may not itself be flexible, a large amount of flexibility can be embedded within this system boundary (on the cluster level) through reconfiguration, change of orbit, change of function based on the new demands, and so on. Therefore, the DSS may be flexible even though the satellites making up the cluster may not be flexible.

In summary, depending on the chosen system boundaries, different values and types of flexibility may be observed in a system. The focus of the present research is limited to technical aspects of space systems assets, which include satellites, spacecrafts, and space telescopes. Flexibility in levels of enterprise, organizational, management, ground facilities and human resources is very important. However, these realms are outside the boundaries of this dissertation on flexibility in space systems, and call for further research.

4.3. System Aspects

Flexibility in a specific system is perceived differently depending on stakeholders' views and interests in the system. Flexibility is therefore always measured with respect to particular aspect within a system. Even within clearly defined system boundaries, a system may be flexible with respect to one aspect, while being inflexible in another. When evaluating flexibility for any system, we have to be aware what aspect or aspect of the system is of interest to us. The aspect of importance to the stakeholder can be an "attribute"[11] or a "general attribute,"[12] change *of* an important function or *to* another function, expansion or reduction of size or capacity of a system, a response to a specific change in the system, or lifetime change. As an illustration, let us consider the case of a GEO telecommunication satellite. Flexibility in the following aspects of the system may be of importance to us (see Figure 4.4):

Lifetime: Can the lifetime of the satellite be extended beyond its designed lifetime if needed? Is it worthwhile launching a new satellite instead of attempting life extension?

Change of mission: Is there enough flexibility in the payload and instruments on board the spacecraft to change the mission of the telecommunication satellite to an imaging mission? Can the satellite be moved and adjusted to operate over a different geographical area, within a different GEO slot?

Expansion: Will it be worthwhile to add new satellites to complement the operations of the current communication satellite?

Partial failure: In case of a partial failure, is it advisable to launch a new satellite or to use on-orbit servicing if available?

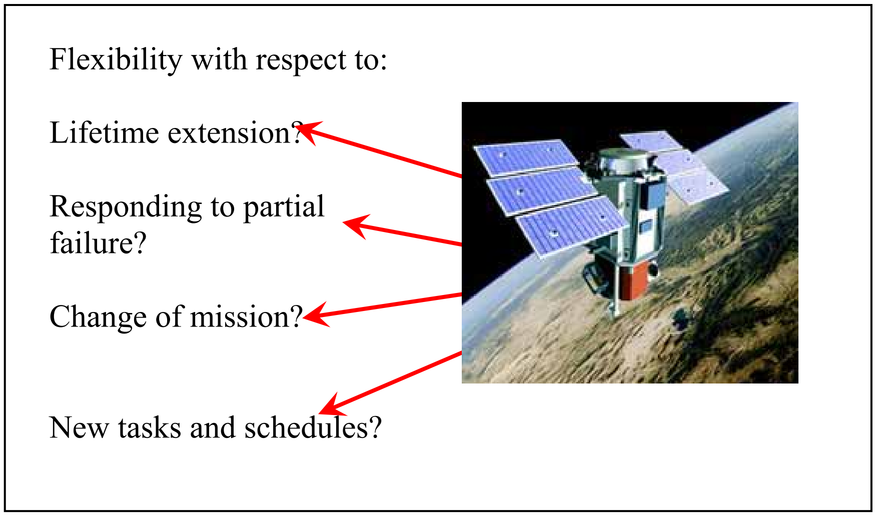


Figure 4.4. Some possible aspects of importance in an imaging satellite.

---

[11] "An attribute is a decision maker-perceived metric that measures how well a decision maker-defined objective is met. Attributes have been described as 'what the decision makers need to consider' and/or 'what the user truly cares about.' In practice, they must also be quantifiable, and capable of being predicted with reasonable fidelity by fairly high-level models. The attributes will be used to determine the utility of the system to the user." (ROSS ET AL. (2004))

[12] INCOSE' "general attributes" are quantity, quality, coverage, timeliness, and availability (INCOSE, 2002).

If our concern is flexibility with respect to an *aspect*, we can define the concept, its component elements, and measure flexibility more accurately. It should be noted that a system shows different amounts of flexibility with respect to different aspects. A GEO telecommunication satellite may show a great deal of flexibility with respect to life extension, while it might not be flexible with respect to responding to partial failure of the system. Also, not all the aspects that may contain some kind of flexibility are of importance to the stakeholder. For example, in the case of a military satellite, timeliness and the availability of the satellite to respond to change of mission may have a vital importance. For the case of a commercial satellite, lifetime and the upgrade to new technologies play an important role, because the goal of the mission is to maximize the benefit to the stakeholder. For the case of commercial remote sensing satellites, timeliness, scheduling and relocation flexibility may be the aspects of importance. A remote sensing satellite may need to be available in case of a new target of opportunity (e.g., an unexpected volcanic eruption, a forest fire) or unexpected difficulties (e.g., clouds blocking a critical target [Pemberton 2001]).

Determining the desired aspect(s) is a key step in defining and measuring flexibility more accurately. If not well defined, the direction of necessary actions to design, or implement flexibility in a space system remains vague. The investment in all possible aspects of flexibility in a system is associated with a very large cost, yet not all aspects of flexibility are desired or even used in a space system.

4.4. Time Window of Change

Time is a key element in definition and valuation of flexibility. A system goes through many changes, aging and degrading with time. When a space system is developed, it is designed to meet the functional requirements of that time. Given that our current space systems cannot modify themselves in face of dramatic changes in the system, they often cannot meet emerging requirements or tackle unforeseen problems.

4.4.1. Time Windows as Temporal Boundaries for Change

Time is an indicator for changes or events that happen to a space system. The choice of time window is important in the concept of flexibility. Depending on the time window chosen, a system may contain different value delivery related events or changes. Shorter time windows focus on the short-term flexibility of a system, while longer time windows focus more on longer-term flexibilities. A specific satellite architecture may show more flexibility in longer time periods, while lacking flexibility in shorter time frames. For instance, a satellite might be flexible enough to cope with market changes in a period of a year, but not enough to adapt to daily or weekly changes in the market. Therefore, the timeframe has to be determined. A time window provides the option of partial flexibility calculations over different time periods within the spacecraft's lifetime. For instance, we may be interested only in evaluating the flexibility of a system from its fifth year in space until the end of its lifetime. This may yield a different flexibility value than for the entire lifecycle.

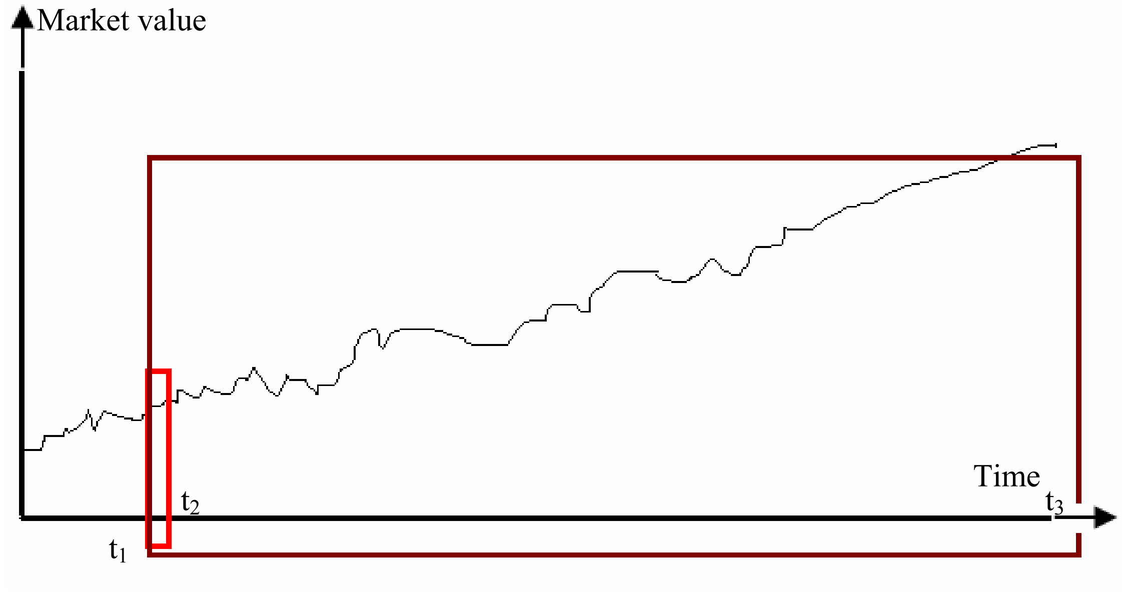


Figure 4.5. Schematic of different time windows in the market

Figure 4.5 shows change in the market value and the progress of change over time. The market shows different behavior depending on the time windows chosen. For example the period between t_1 and t_2 contains the ups and downs of the market in one week, while the time window between t_1 and t_3 contains the events in the market for a period of 6 months. Bigger time windows may have more focus on the general trend or major changes in the market, while smaller time windows may deal with more detailed changes in the market. Time windows also contain events, decision and chance nodes. If a decision tree analysis (DTA) or a similar tool is being used, depending on the time intervals between decisions, a time window may contain several decision and chance nodes. A schematic of decision tree analysis and the impact of time window selection can be seen in Figure 4.6.

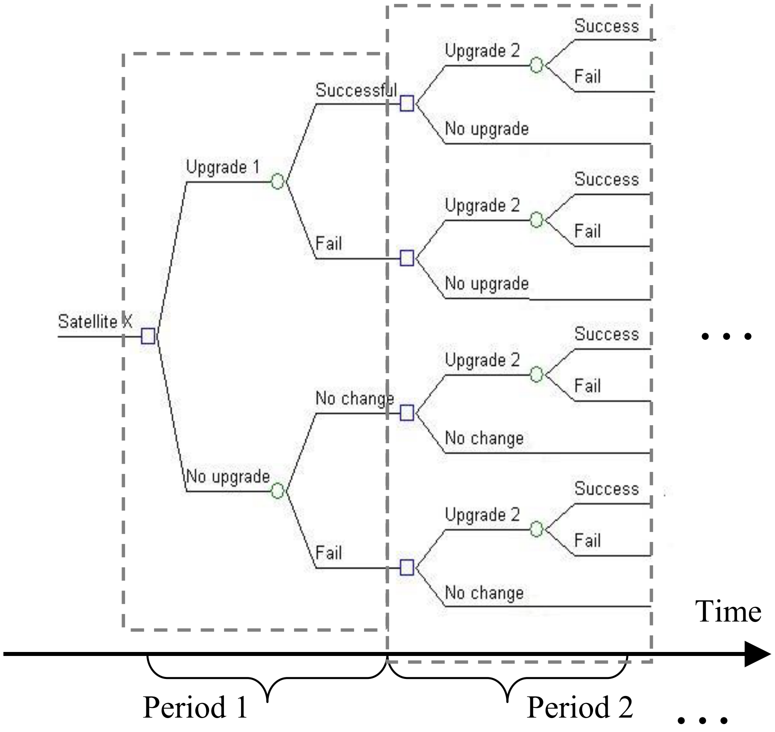


Figure 4.6. Schematic of time windows and the events they contain in a DTA

4.4.2. Short, medium, and long-term flexibility

Based on the selected time window, different types of flexibility can be observed in the system. If a system can respond to changes in a short period of time, for example, it can show timely response to emergency or partial failure (hours, days, months); it has short-term flexibility. If a system can cope with changes over longer periods of time for example, coping with market changes (months, a year), it has medium-term flexibility. In cases where flexibility is required for very long periods of time, for example, the lifecycle of a satellite (years), it becomes a long-term flexibility.

4.4.3. Lifecycle Flexibility

From the point of view of this research, the lifecycle of a space system is divided into two major parts: pre-launch and post-launch, which can be seen in Figure 4.7. In the pre-launch time window, different phases of concept development, preliminary design, detailed design, testing, and production can be observed. In the design and production phase, flexibility can be designed into the system, as discussed in chapter 5 of this dissertation. The operation phase or post-launch is the showcase for displaying the flexibility implemented into the space system in the design phase. The system may show flexibility post launch even if the flexibility has not been designed into the system intentionally (rather emerging as an unforeseen side-benefit of the design). Even when flexibility has not been designed into a system initially, the possibility of applying flexibility may often still exist. On-orbit servicing, software upgrades, and other emerging ideas provide a range of options for “inserting” flexibility into the system.

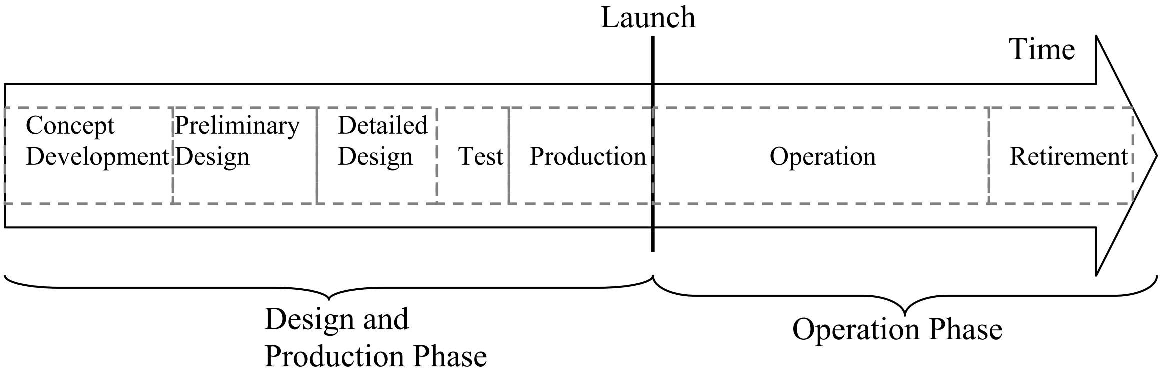


Figure 4.7. Pre-launch and post -launch time frames

4.5. Uncertainty

Uncertainty is the hallmark of all complex systems. It is the lack of complete knowledge of the state of a particular system in the present or in the future. There are many drivers of uncertainty, but basically it is due either to natural laws (e.g., Heisenberg’s uncertainty principle), lack of time or resources to explore the system, emergent behavior of the system, or other cognitive limitations. While uncertainty has traditionally been viewed as a negative aspect of a system, it can also be viewed as an opportunity. Flexibility is the ability of a system to take advantage of uncertainty to sustain or increase its value delivery. In the following sections, we will look at the different aspects of uncertainty and their role in the nature of flexibility.

4.5.1. Roots of Uncertainty

The roots of uncertainty are categorized in the literature as lack of knowledge, lack of definition, statistically characterized phenomena, known unknown, and unknown unknowns (McManus 2004).

Lack of knowledge includes facts that are not known, or are known only imprecisely. This type of knowledge can be gathered and the uncertainty can be reduced. Lack of definition is a type of uncertainty that exists when the elements or attributes of a system are not specified. Statistically characterized (random) variables or phenomena are things that cannot always be known precisely, but can be statistically characterized, or bounded. An example of known unknowns is market uncertainty: we know the uncertainty exists, but we cannot reduce the uncertainty beforehand. Unknown unknowns may be emergent behaviors of a system; we are not even aware of their existence until they happen to the system.

These roots have different levels and depth of uncertainty. For example, the uncertainty associated with the lack of knowledge and definition is much less than the uncertainty associated with unknown unknowns. Figure 4.8 conceptually shows the depth of uncertainty in these five defined categories of uncertainty.

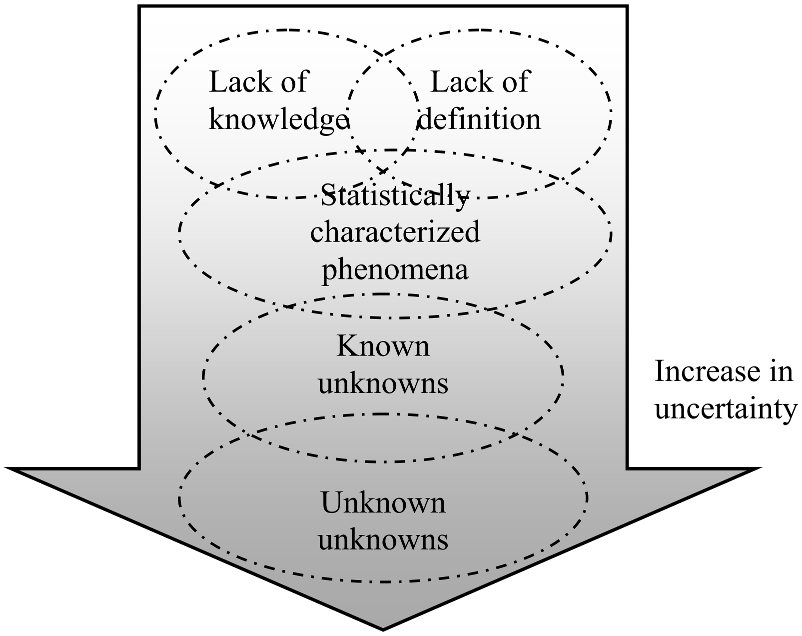


Figure 4.8. Schematic of the depth and level of uncertainty in a system

4.5.2. Uncertainty and Space Systems

Within the boundaries of this thesis, which deals only with physical aspects of space systems, many types and sources of uncertainty can be observed. Uncertainty may exist in the system or in the environment. Except for the unknown unknowns, the other types of uncertainty can be recognized and in some cases bounded. The master plan for designing flexibility in a space system begins with identifying sources of uncertainty and, in the next step, how to deal with uncertainty.

A) Uncertainty in technological innovation

The long time it takes to get a space system from design to launch can result in the use of technology that is already outdated by the time of launch, let alone during the lifetime of a space system. A classic idea in this sense is Robert A. Heinlein’s story of a colonization mission with sub-light speed technology, where the intergenerational spaceship arrives at the planet only to find the planet inhabited for hundreds of years by earth colonists who departed Earth with much better technologies centuries after the initial departure.

B) Lack of sufficient knowledge from physical environment

Our knowledge of space and planetary environments is still very limited and therefore a spacecraft is faced with uncertainty in the physical environment. Lack of proper knowledge of the environment may cause a partial or total failure of the mission. This type of uncertainty can be reduced through gathering more information from several missions. A spacecraft is exposed to many environmental hazards in space, some of which are little understood. Some examples of such hazards are atmospheric drag, ionizing radiation, impact by meteoroids and orbital debris, accumulation of electrical charge, presence of surface contaminants, atomic oxygen, and damaging ultraviolet photons. The uncertainty associated with environmental hazards can be reduced by acquiring more information on the space environment.

C) Known unknowns

There is always an uncertainty associated with the likelihood of failure of a part or component. The advertised lifetime of a component is usually based on the statistical average lifetime of the component. The uncertainty in performance of the space system can be reduced through testing it. (It should be mentioned that there are many unknown interactions between different components of a spacecraft _unknown unknowns_ which may or may not be observed during the testing process.)

In addition to the above, one of the major sources of uncertainty in space systems is market uncertainty. Specifically for the case of commercial satellites, market uncertainty is the most important source of uncertainty. A flexible space system can cope and adapt to changes in the market through expansion or contraction of its capacity, or upgrade and change of functionality on board a spacecraft. For example, in the case of a higher demand for data transfer through a cluster of satellites, the number of satellites can be increased and the cluster can be reconfigured. Another approach could be the upgrading of the satellites with better technology, if available. The market may also become saturated with a specific service after a while, or the service may become obsolete. A flexible space system may be able to make a transition from its current service to a new on-demand service.

In some cases where enough history of the market exists, the market can be modeled and the system can be designed to be flexible enough to cope with the likely future uncertainty. Currently, several approaches to modeling exist, such as random walk theory, portfolio theory, CAPM theory, neural networks, and others. There are also several suggested ways of coping with and taking advantage of market uncertainty, such as real options "in" and "on" the system, which will be discussed in the next chapter.

D) Emergent behavior or unknown unknowns

Space systems are complex systems. Complex systems have properties or behaviors that are sometimes not intended or planned for. Such unforeseen properties of a system are emergent properties (Moses 2004). The emergent properties of a system may be desirable or undesirable.

Some Examples of Space Systems Uncertainty

The following cases illustrate the above concepts, as they apply to actual space systems.

A) Commercialization of GPS constellation

GPS constellation is an example of desirable properties of a system. The original use of GPS was a military positioning, navigation, and weapons aiming system. The first GPS satellite was launched in 1978. In 1984, President Reagan announced the partial availability of the GPS satellites to the civilian community. The civilian market for GPS was an emergent market, which was not foreseen at the time of design and launch of the satellites. Some emergent applications of GPS include intelligent transportation systems, navigation for aviation and maritime uses.

B) Mars Rover Opportunity power boost[13]

A series of unexpected environmental effects swept dust on the solar panel of the Mars Rover Opportunity. Both Mars Rovers, Spirit and Opportunity, landed on Mars in January 2004. They originally had more than 900 watt-hours of energy per sol, which was expected to degrade due to dust deposition on the solar panels. After a year of operation, Spirit's

---

[13] New Scientist article, December 23, 2004.

power output has dropped to 400 watt-hours per sol, while Opportunity has regained its original power (900 watt-hours per sol). It is speculated that a part of this difference between power outputs is due to dust removal through surface wind.

C) Mars Polar Lander catastrophic failure

Mars Polar Lander (MPL) was a part of the Mars survey program and was launched in January 1999. The spacecraft was destroyed in the process of landing. The most suspected reason for failure is the entry, deployment, and landing sequence, in which three landing legs were supposed to deploy from stowed to landing condition. Each of the legs was fitted with a Hall Effect magnetic sensor which would generate a voltage when the legs contacted the Mars surface and shut off the descent engines after the touchdown. The touchdown sensors generated a false momentary signal at leg deployment. This was an emergent behavior in the system. The spacecraft software interpreted the signals generated at leg deployment as a valid touchdown signal. As a result, the software shut off the engines at an altitude of 40m and the Lander free-fell to the surface and was destroyed (Leveson 2004).

D) Teledesic Space System

The Teledesic Space System was supposed to provide global broadband internet access and voice and digital data services. The original design of such a system was developed in 1994, with a constellation of 840 satellites in low Earth orbit at a development cost of $6.3 B. The high market uncertainty and the initial huge capacity of the system led to a new design for the constellation by 1998, a system with 288 satellites on orbit. By February 2002, the system had shrunk to 12 operational satellites in medium Earth orbit at a development cost of $1B, with 18 additional satellites planned for later to supplement the coverage.

4.6. Access

In order to design or implement flexibility into a space system after launch, having access to the system is a necessity. Access is defined as “permission, liberty, or ability to enter, approach, communicate with, or pass to and from a system"[14]. Here, access is defined as the ability and means to communicate, interact, and create the desired change in a space system.

The access to a system is important for creating or taking advantage of a designed flexible option in a system. The availability of access to a system may be considered rudimentary in some engineering systems, because access to the system exists almost all the time. For example, in case of an infrastructure such as a road system, even after the system is operational, desired changes and flexibility can be implemented into the road system. The importance of having access to implementing flexibility in a space system comes from the inaccessible nature of the space system after it is fielded. The Earth's orbit, and space in general, is an underdeveloped environment and not many infrastructures exist in space. The lack of servicing infrastructure or frequent launches makes the space system less accessible after it is launched. Large physical distances in space and orbital mechanics are the natural barriers that can block the access to a space system.

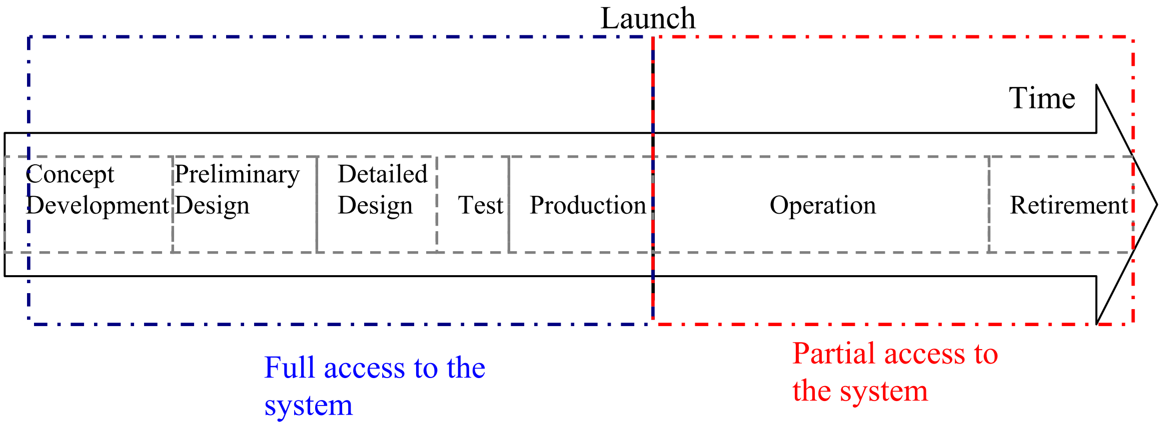


Figure 4.9 Pre launch and post launch level of access to the system

4.6.1. Types of Access

The post launch access to the system is usually partial or discontinuous. We define two levels of access to the system: physical and information access. Physical access is available when a desired change or correction can be achieved through physical manipulation,

---

[14] Encyclopedia Britannica

intervention, or change of a space system. One example of physical access is the Hubble space telescope servicing missions. Since 1993, NASA astronauts have performed four space shuttle servicing missions on the Hubble space telescope. The Hubble space telescope (HST) has gained flexibility by extension of its operating life through the replacement of aging hardware, and the enhancement of its scientific capability by very large factors through the installation of advanced science instruments incorporating new cutting-edge technologies. Maintaining and upgrading the telescope was an option designed into the Hubble mission plan. That option was created by a modular telescope design, which permitted astronaut-friendly servicing operations. Still, all the technical flexibility in the world did not save the space telescope from the impact of budget cuts. The HST is supposed to be de-orbited by 2006.[15]

The high cost of physical access to a space system after launch has opened the doors to options created through information access to the space system. Software provides the opportunity to create a limited access to space systems. Some upgrades and change of function can be performed through modifying the software of a space system. As an example of such a means to create access to a space system, the Galileo spacecraft can be mentioned. The high gain antenna (HGA) of the spacecraft was supposed to open on the spacecraft's journey to Jupiter, but it failed to open. All the attempts to correct the partial failure of the Galileo were fruitless, and there was no possibility of physical access to the spacecraft. But through information access, the software of the spacecraft was modified to use the low gain antenna (LGA) instead. The HGA was supposed to provide 134 Kilobits per second, while the LGA was providing only 8-16 bits per second. Through implementation of sophisticated data compression techniques, data throughput was increased to 160 bits per second and the mission was rescued from complete failure.

4.6.2. Limits of Physical Access

After a space system is launched, physical access to the space system becomes very limited. If the space system has an interplanetary mission, the physical access to the system

---

[15] http://www.cnn.com/2005/TECH/space/01/24/hubble.funding/index.html

is zero at the moment, because of lack of infrastructure in place. Also, the orbital transfers and trajectories create a time lag in accessing the space system, especially in contingencies. For space systems orbiting the earth, physical access is more possible. With a servicing infrastructure in place, a space mission can be accessed and modified. In case of a lack of infrastructure on orbit, a manned or a robotic mission can be launched. The level of physical access before and after launch can be seen in Figure 4.9.

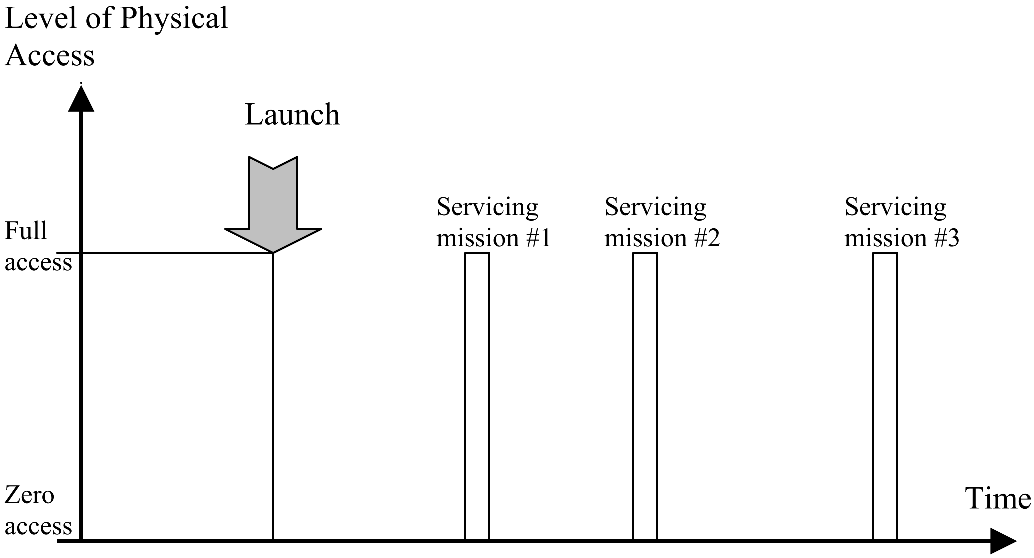


Figure 4.10. Levels of physical access in a space system before and after launch

4.6.3. Limits of software and information access

Information access to a space system is not continuous in time, and depends on the space system's orbit, trajectory, and distance from the Earth, and the basic hardware on board. If a spacecraft is in an interplanetary trajectory, a time lag of information and command transfer exist. For example, a round-trip communication to the Voyager 2 spacecraft takes almost a day. In the case of Mars rovers, a communication delay is estimated to be between 6 and 40 minutes. In case of satellites on earth orbit, the information access depends on the satellite orbit. A time in view is associated with each satellite, in which the modification and access can be performed during one or several windows.

The onboard spacecraft hardware is another important limiting agent in manipulating a space system. The range of possible modifications and changes to a space system depends on the existing hardware and the possible functions it performs. For example, in the case of

Galileo spacecraft, if the low gain antenna (LGA) had not existed on board spacecraft, no amount of software change and upgrade could have saved the mission from failure.

4.7. Response to Changes in Value Delivery

The response to change in value delivery of a system is the most important element in the study of flexibility. Most of the information related to the response to change in value delivery of a system is used in the next chapter to construct a measure for flexibility in space systems. A system is exposed to many changes and events at any given moment in time, but not all of these changes are of importance to the concept of flexibility. A set of changes and events associated with the *change of value delivery* are the key events in constructing a measure for flexibility. For example, the function of a spacecraft computer includes a set of different daily functions, which do not have any effect on the value delivery of the spacecraft. However, if a partial failure happens to the spacecraft computer or the need for processing power increases, the event becomes of importance from the point of view of flexibility, because it is associated with change in value delivery of the system.

A change in value delivery of a system may be followed by a response to that change, and a response is often associated with a certain cost to the system. *The existence of a proper, timely, and cost-effective response is the difference between a flexible and a rigid (non-flexible) system.* A response should be able to increase the value delivery or limit the loss of value to a system. It should also be performed in a timely manner in order to capture more value to the system or limit the losses. Some examples of space systems and responses are discussed here.

4.7.1. Iridium Satellite Systems

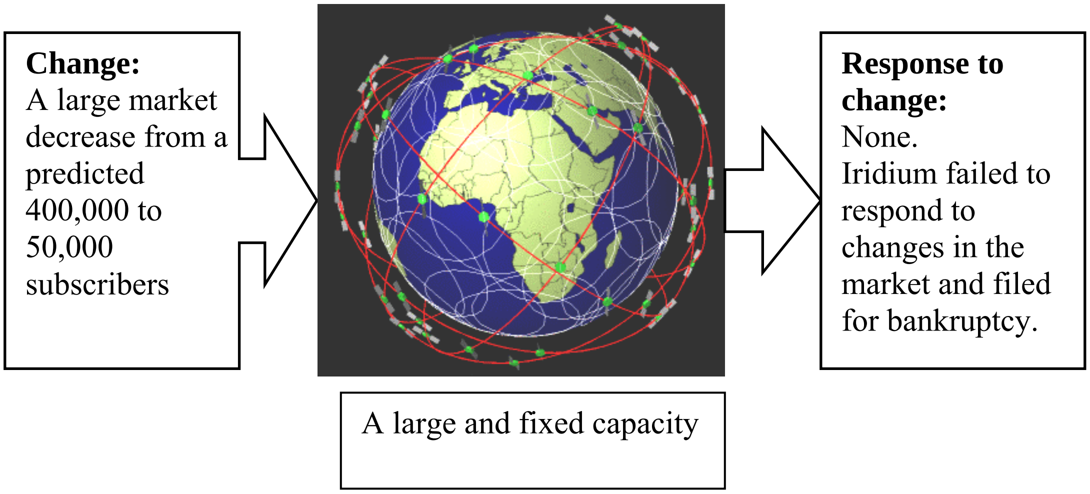


Figure 4.11. Iridium satellite systems in face of change and its response to change.

A) Change in value delivery: Change and shift of market.

Iridium is a telecommunication satellite system which provides global mobile telephone services. The Iridium constellation consists of 66 operational and 14 spare satellites in a constellation of six polar planes. The system is a great success from the point of view of technical design. Iridium began commercial telephone and satellite-paging services in the late1990's based on the assumption of a high number of subscribers, and consequently a high cash flow. Most of the satellites were launched in 1997 and 1998 and the cost of the network was $5 billion. The target market was emerging international travelers who needed global phone services at any location and time. The estimated market for the Iridium satellite system was 400,000 subscribers at the time of design. But by 1999 Iridium had only 10,000 subscribers due to the lack of demand. The lack of demand was due to the inability to compete with mobile satellite system companies such as Global Star, Teledesic, ICO global communication, and ORBCOMM. The rapid grow of the ground-based mobile networks was another reason for its market decline.

B) Response to change: None.

Iridium satellite system was unable to adapt to new market conditions and other changes. Due to the lack of demand and high competition, Iridium filed for chapter 11 bankruptcy protection. In the year 2000, Iridium terminated its services and was faced with the decision to deorbit the satellites. The estimated bankruptcy was $2.2 billion dollars. In 2001, a consortium of private investors pulled the system from bankruptcy for $25 million dollars.

4.7.2. Galileo Spacecraft High Gain Antenna (HGA) Failure

Change:
Galileo's high gain antenna failed to open. The information could not be transferred back to Earth.

A low gain antenna was designed into the system.

Response to change:
Through change of software, the low gain antenna was used to transfer the information back to Earth. Instead of a total mission failure, 70% of the original mission goal was achieved.

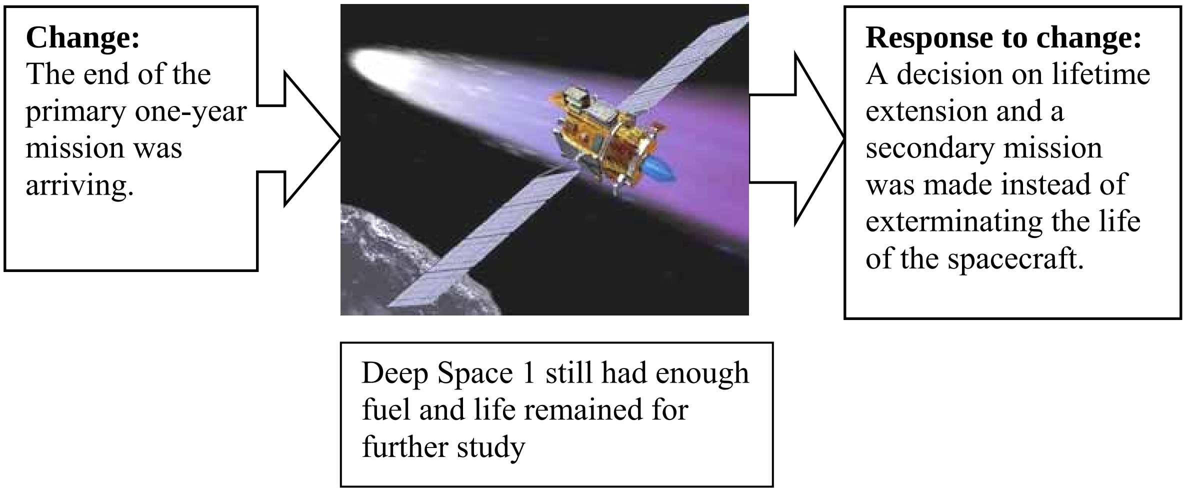
Figure 4.12. Galileo's spacecraft in face of partial failure and its response to change.

Looking at the Galileo case, one can again see the change in value delivery and the impact of the relevant flexible response.

A) Change in value delivery: The high gain antenna did not open at the scheduled time. Without a response to this problem, the mission to Jupiter would be facing total failure and the mission value would be lost.

B) Response to change: New software was designed and uploaded to the spacecraft on its way to Jupiter. The new software took advantage of the existing low gain antenna (LGA) to transfer more of the information back to Earth. The result was the recovery of a large part (approximately 70%) of the original mission value.

4.7.3. Deep Space 1 Extended Mission



Change:
The end of the primary one-year mission was arriving.

Response to change:
A decision on lifetime extension and a secondary mission was made instead of exterminating the life of the spacecraft.

Deep Space 1 still had enough fuel and life remained for further study

Figure 4.13 Deep Space 1 extended mission to study comet Borrelly.

A) Change in value delivery: Deep Space 1 mission was originally designed to test 12 new technologies on board the spacecraft. After the end of the one-year original lifetime, the mission was supposed to discontinue its value delivery.

B) Response to change: Deep Space 1 had enough available fuel and lifetime to perform an extended mission. The spacecraft software was changed and uploaded in Deep Space 1 to perform a rendezvous with comet Borrelly and study the comet. The length of the extended mission was two years.

The types of responses to change in value delivery of a space system are numerous. For example, a response can be designed to fix, reconfigure, relocate, extend/terminate lifetime, expand, contract, and upgrade a space system. There are many forms of responses to change that can be designed to cope with or take advantage of change in a space system, depending on the condition of the system. A set of examples of some conditions and the relevant types of responses can be seen in Table 4.1. A space system may need a combination of these responses or a custom-made response to change.

Table 4.1. Change and Response to Change in Space Systems

Conditions that result in change of value delivery of a space system	Response to change
A partial fixable failure happens	Fix
A space system is needed in a different geometrical position	Relocation, reconfiguration, plane change
A different communication link structure is needed	Change in information structure
An increasing market demand exists	Expansion
A decreasing market demand exists	Contraction
At the end of a space system lifetime, the system is still functional for a longer period of time	Life extension
The operation costs are much higher than the benefits gained	Termination
New technology can substantially increase the utilities or benefits gained	Upgrade

In order to measure changes and responses to value delivery of a space system, a measuring tool is necessary. In this research, we are looking at the responses to change through the lens of financial analysis. Changes and responses to changes are measured in the forms of costs, monetary/non monetary benefits, and utilities associated with them. We therefore study a projection of the system in financial and economics dimension and its progress in time. Schematics of this concept can be seen in Figure 4.13. Changes and responses are mapped into the economic dimension through cost, benefit, utility and payoff profiles of a space system over time. In the next chapter, this information is used to measure the value and magnitude of flexibility in a space system.

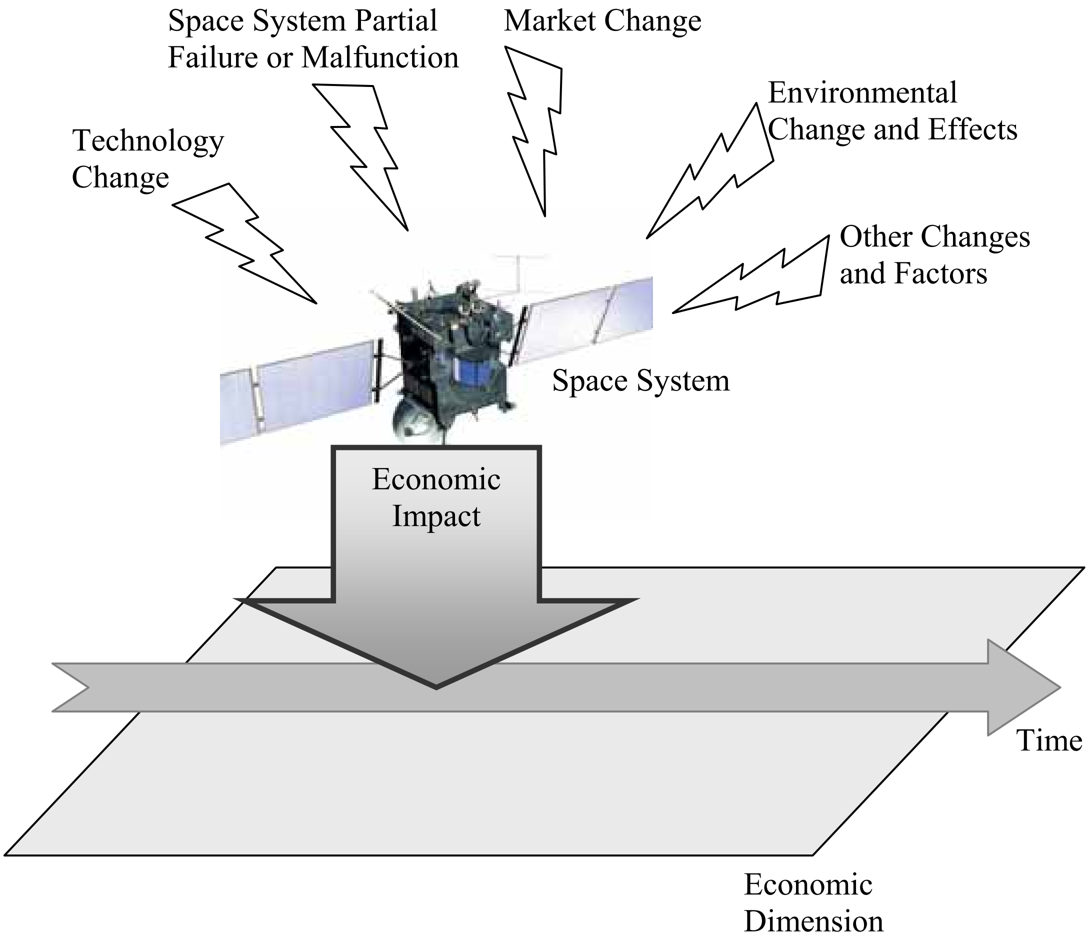
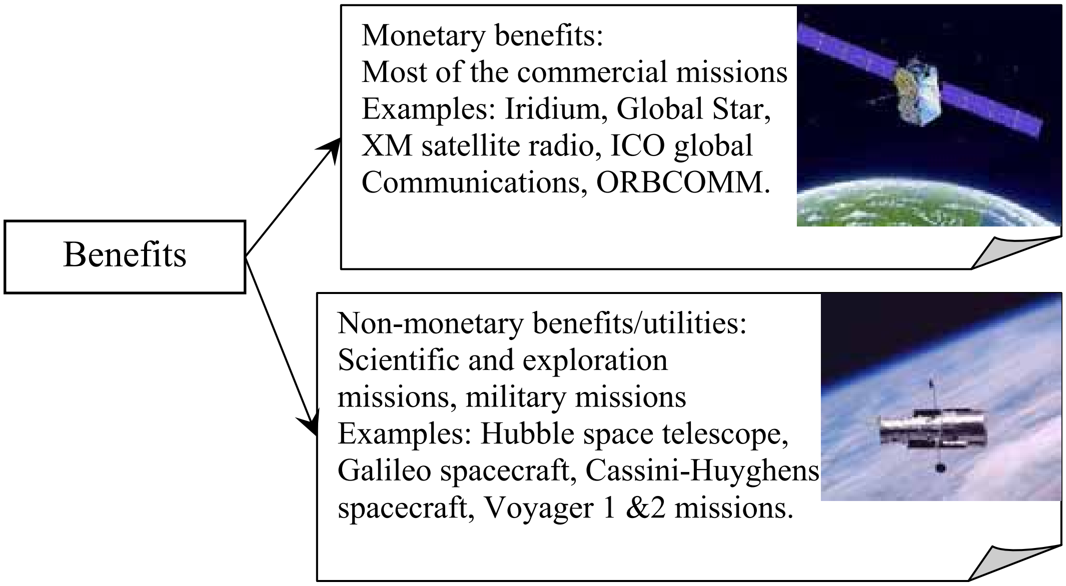


Figure 4.14. Potential changes in a space system and their projection onto the economic dimension

The benefits generated by a space system may not be measurable through monetary evaluation. In the case of commercial satellite systems or missions, the generated benefit and value can be measured in monetarily. But for scientific and some military missions, the generated value may not be measurable monetarily. In most cases much information is lost in the process of determining a monetary value for the produced benefits of a system. For example, consider science and exploration missions.



Monetary benefits:
Most of the commercial missions
Examples: Iridium, Global Star, XM satellite radio, ICO global Communications, ORBCOMM.

Non-monetary benefits/utilities:
Scientific and exploration missions, military missions
Examples: Hubble space telescope, Galileo spacecraft, Cassini-Huyghens spacecraft, Voyager 1 &2 missions.

Figure 4.15. The division of benefits to monetary and utility (non-monetary) benefits.

In order to quantify the non-monetary benefits of a space system, a prospect theory approach is taken here. Traditionally, utility theory has been used instead. Utility is one of the basic ways of representing non-linear preferences for possible benefits and losses. This approach is very useful because “people usually do not attach the same value to each unit of benefit they receive or of cost they pay” (de Neufville 2004). Thus, utilities capture how much they desire various values of the attributes in quantifiable ways. Utility functions are the result of a set of assumptions and are applied to situations involving uncertainty. They are routinely used in decision analysis.

The utility function $U(x)$ is a type of value function whose units have relative meaning to each other. The utility function exists in a particular cardinal scale on which values can be calculated meaningfully. The scale of utility is the ordered metric scale. In this scale the units are constant, identifiable amounts which can be combined linearly by addition, subtraction, or averaging. However, zero on an ordered metric scale has no absolute meaning; it acts just as a reference point. Measurements of utility on an ordered metric scale can be transformed into equivalents by a positive linear transformation:

$$U'(X) = aU(X) \pm b$$

Where $U'(X)$ and $U(X)$ are strategically equivalent (de Neufville 1990). Traditionally, in calculations of utility, a dimensionless scale from zero to one is used. The utility is considered zero for the least desirable acceptable level and is defined as one in highest desirable level. Some Typical forms of utility functions can be seen in Figure 4.15.

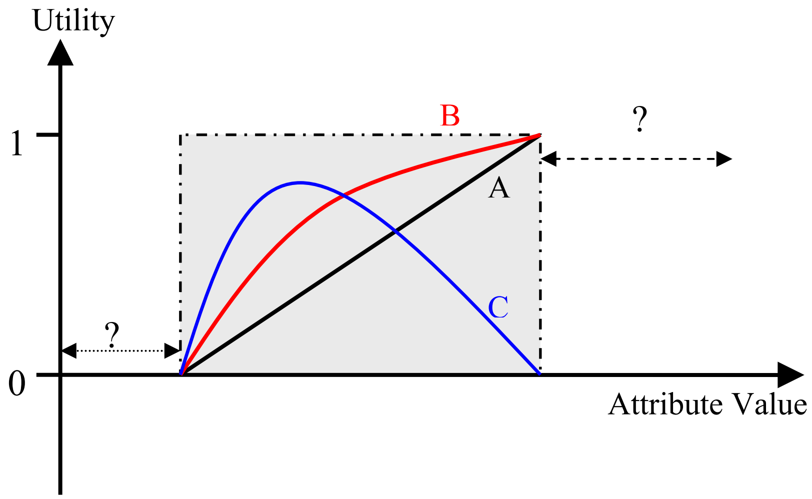


Figure 4.16. Some different types of utility function (A: linear, B: diminishing returns, C: non-monotonic). Utilities less than zero and more than one are not usually determined. (Adapted from SSPARC)

In flexibility calculation of a system, the values of utilities over one or less than zero are frequently required. As can be seen in the grey box of Figure 4.15, we can only be concerned with the current range of zero to one of the utility. The boundaries of the box changes with time, because the range of desirability of an attribute may change with time. For example, the memory range of a commercial integrated circuit changes every 9 months and its today's utility is considered out of the range of utility of the system a year before. Utility theory cannot capture the extra benefit gained in a flexible system. Therefore, there is a need for a better value-capturing system.

We suggest using a prospect theory approach to deal with shortcomings of the utility theory in capturing the extra benefits of a system. The definition, benefits and methodology of the prospect theory is discussed in detail in Chapter 5 of this thesis.

Summary

In this chapter, we took a unique approach to identifying common elements of flexibility in space systems. The elements that were discussed included:

- System Boundary
- System Aspect
- Time Window
- Uncertainty
- Access and Implementability
- Responses to Change in Value Delivery

We argued that a comprehensive measure for space systems flexibility should account for these elements. Furthermore, we looked at different cases where each of the above elements were dominant features of flexibility in space systems. An important takeaway from this chapter is the proposition that flexibility is not used to address all types of change in the system; rather it is only geared towards addressing changes that impact the system's value delivery over its lifetime or a fraction thereof.

Based on the insights of this chapter, we develop a comprehensive framework that accounts for the-above-mentioned elements and that can address many aspects of flexibility in space systems.

References:

(de Neufville 1990)
de Neufville, Richard, “Applied Systems Analysis: Engineering Planning and Technology Management,” McGraw-Hill, New York, 1990.

(de Neufville 2004)
ESD.71 lecture notes by Prof. Richard de Neufville, Fall 2004, Massachusetts Institute of Technology.

(INCOSE 2002)
INCOSE Systems Engineering Handbook: A "How To" Guide for All Engineers, 2nd ed., International Council on Systems Engineering, Seattle, WA, 2002.

(Leveson 2004)
Nancy G. Leveson, “Role of Software in Spacecraft Accidents,” Journal of Spacecraft and Rockets 2004, 0022-4650 vol.41 no.4 (564-575)

(Marr 1994)
Marr, J.C., IV, “Performing the Galileo mission using the S-band low-gain antenna,” Aerospace Applications Conference, 1994. Proceedings, 1994 IEEE, 5-12 Feb. 1994, Pages: 145 – 183.

(McManus 2004)
McManus, H. and Hastings, D. E., “A framework for understanding uncertainty and its mitigation and exploitation in complex systems,” Engineering Systems Symposium, 2004.

(Moses 2004)
Moses, J., “Foundational Issues in Engineering Systems: A framing Paper,” Engineering systems monograph, march 2004.

(Pemberton 2001)
Pemberton, J.C.; Galiber, F., III, “A constraint-based approach to satellite scheduling,” Constraint Programming and Large Scale Discrete Optimization. DIMACS Workshop, 2001, p 101-14

(Shaw et al. 2000)
Shaw, G. B., Miller, D. W., and Hastings, D. E., “Generalized Characteristics of Satellite Systems,” Journal of Spacecraft and Rockets, Vol. 37, No. 6, 2000, pp. 801–811.

Chapter 5

5. Measuring the Flexibility of Space Systems

WHAT emerges as an important conceptual understanding of flexibility, is that one could define flexibility as the ease of upward movement in the value delivery of a system over its lifetime. Here ease refers to the ability of the system to overcome resistance (cost and physical constraints), or in other words the cost-effectiveness of moving upwards on the value delivery curve.

In the previous chapter, we discussed the basic elements for measuring flexibility. These included the boundary of the system to be studied, aspects of the system to which flexibility is applied, time window in which flexibility is observed in the system, the uncertain and probabilistic nature of the future of the system, the degree of access to the system in order to apply the option or flexibility, and responses of the system to change through changes from the owner's, designer's, operator's and user's perspective in the value delivery (see Figure 5.1).

In this chapter, we will use these elements as a basis to propose and construct a framework to capture the benefits and costs associated with having various degrees and types of flexibilities in a space system.

We will then use our basic new framework, called the 6E (E for element) framework, in an initial design tradespace and further expand the framework to incorporate space systems in the post-design stage. This includes space systems that are already designed, manufactured, or even launched and operational. In this way, we can capture and measure the value of flexibility for space systems over their entire lifecycle. The 6E framework discussed in the first half of this chapter is useful for capturing the value of flexibility in the operation phase of a space system. In the second half of this chapter, the 6E framework is merged with MATE (multi-attribute trade-space exploration) in order to create and capture flexible architectures in the design phase. The merged methodology is named FlexiMATE.

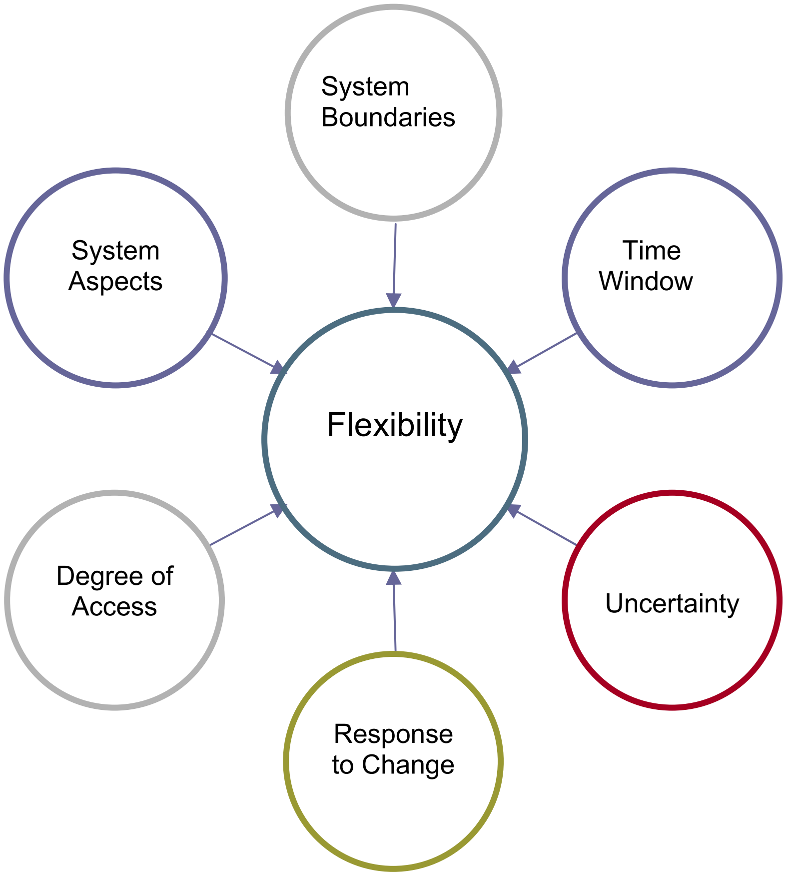


Figure 5.1. Crucial elements in building the flexibility framework

5.1. The 6E Flexibility Framework

Based on a synthesis of insights from the extensive literature on engineering systems flexibility, and the six elements defined in the previous chapter, we propose the 6E flexibility framework to capture the benefits of flexibility at different physical and temporal scales. The 6E flexibility framework takes into consideration the relevant type of uncertainty of the system's future and has a cumulative view of the space system's benefits and costs over its lifetime. Probabilistic future events that may happen to the system are studied in a defined time window, which starts from the beginning lifetime of the system and extends to its disposal. As shown in Figure 5.2, the 6E flexibility framework is a twelve-step process. The steps are as follows:

1. Define system aspect(s) of interest from the point of view of flexibility
2. Define the boundaries of the space system to be studied
3. Define the time window in which the system is studied
4. Identify the relevant sources of uncertainties with respect to the chosen aspect(s)
5. Define the measurable benefits produced by the space system
6. Create a baseline case and a possible set of alternatives based on the degree of access to the space system
7. If an alternative necessitates changes in the original design, then calculate the changes in the original design. If not, proceed to the next step
8. Choose an evaluation method based on the specified types of uncertainties the space system is faced with
9. Calculate the expected benefits and the expected costs associated with the baseline and each alternative case
10. Calculate differences of expected benefits and expected costs for each alternative relative to baseline
11. (optional)- If non monetary benefits exist, prospect theory can be used to capture the *value* of extra benefits to the stakeholder
12. Create a tradespace of Δcost versus Δbenefits or prospect values. Each point in this tradespace shows an alternative's *extra value* gained versus its associated extra cost.

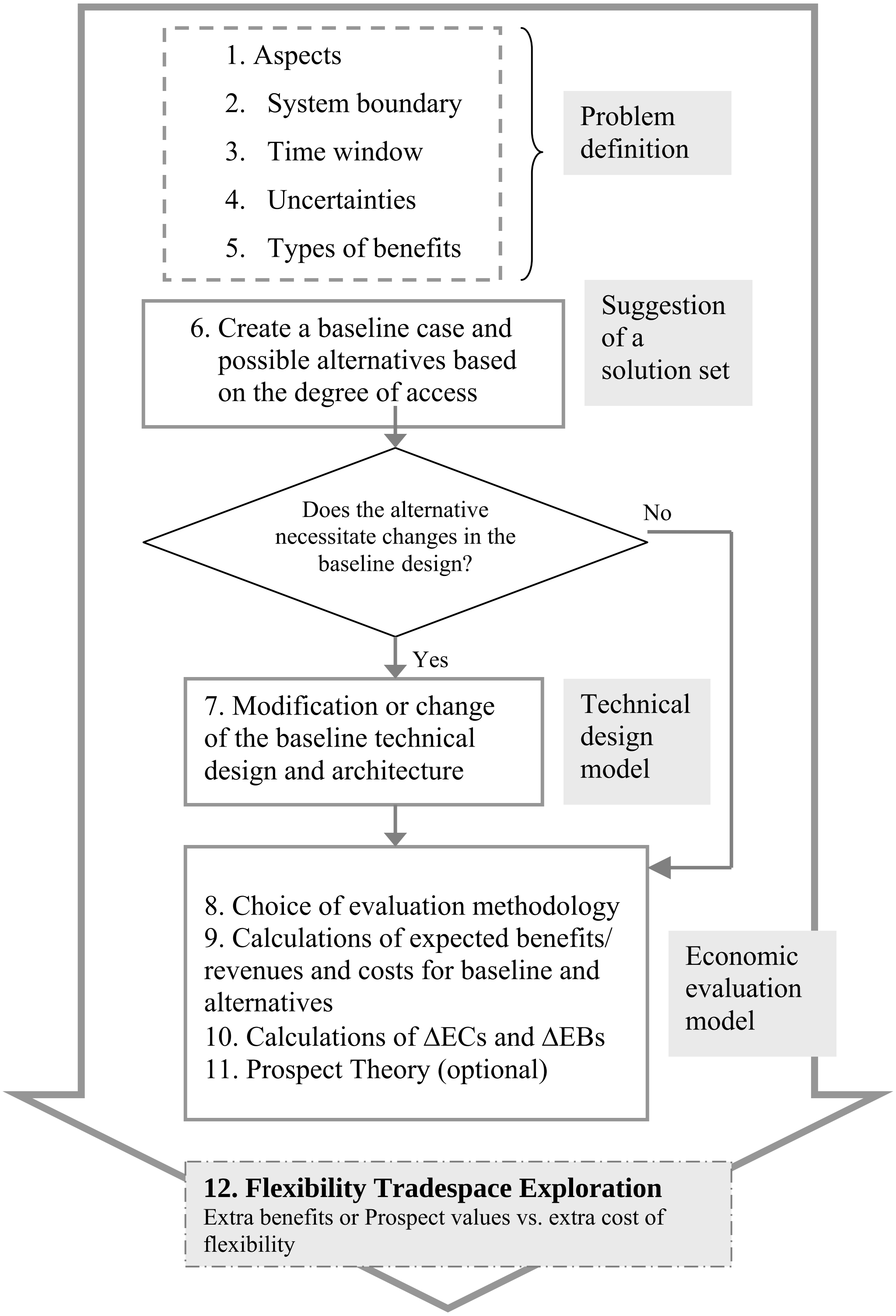


Figure 5.2. The 6E flexibility framework in a nutshell

5.1.1 Defining the System Boundary and Time Window

The first important step in the 6E framework is to clarify the system boundary and the time window of interest to the stakeholder. The system's boundary is a container of the physical space system asset including non-physical information content. The time window is also a container of events and changes that affect the performance and the value produced by the system. Both of these elements of flexibility can be viewed as a type of container: one contains the system of interest and the other contains the scenarios and events.

As an example, we can consider the case of on-orbit servicing of satellites. Based on the chosen boundary of the system, on-orbit servicing can be viewed from two different points of views:

- *The system boundary contains the servicing structure*. We define the servicing structure as Orbital Transportation Network (OTN). OTN is composed of satellites, orbital maneuvering vehicles, fuel depots, and service stations, connected to one another through a cargo transportation network in planetary orbit. Such a system will enable the refueling, repairing, upgrading, and tugging of commercial, scientific, and military satellites and other space units such as space telescopes, with the aim of extending the lifetime and therefore the usefulness of these units.

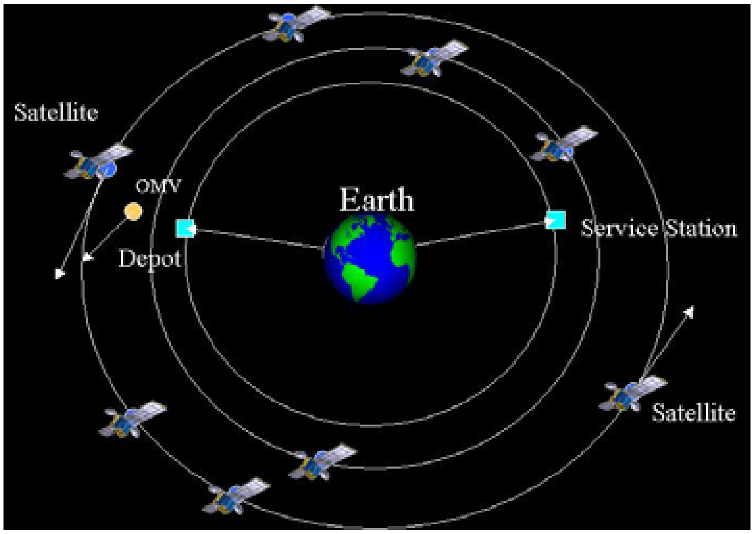


Figure 5.3. Orbital Transportation Network schematic.

- *The system boundary contains the customer satellite(s)*. In this case the boundary of the system is drawn around the customer satellite(s) to be serviced.

Based on the system boundary selected, different issues of importance show up in each system. If the system boundary contains OTN, we are faced with the provider side of the service to the customers. The stakeholder of such a system cares about being able to provide a timely servicing mission to the customer with a low risk of servicing failure, to capture most of the servicing market, to expand the OTN system in case of high market demand, and to change the type of service or the function of the OTN structure to a new function if the market demand shifts from current demand to a new emergent demand. The assumed time window for OTN can be as small as hours to observe the emergency flexibility in the system or as large as tens of years in the case of looking at the long-term visions and the ability of the OTN system to adapt to future changes.

In case the system boundary contains only the customer satellites, we are looking from the customer perspective. The boundary of the system may contain one or more satellites in a cluster or constellation to be serviced. The stakeholder may care about refueling, upgrading, repairing, life extension, and tugging of the satellites. The time window of importance can extend to the lifetime of the satellite, or beyond the original lifetime, if life extension is possible through performing servicing on the satellite.

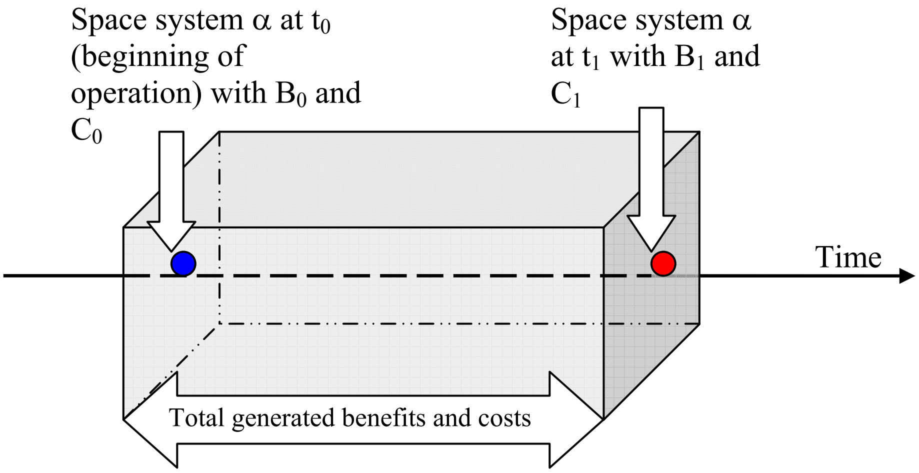


Figure 5.4. An abstract demonstration of a space system in a chosen time window

Figure 5.4 shows two states of the space system. The first is the state of the system at the beginning of operation, or the beginning of the time window, and the second state is at the end of the time window of interest. Both states have information about the produced benefits per unit of time and the total cost of the system at both states. The chosen time window contains the events and changes that have effects on the value delivery of the space system. Therefore, the time window acts as a container of the system and the possible probabilistic events in it. The time window is used in subsequent steps to gather the cumulative probabilistic expected benefits and expected costs of the system.

5.1.2 Defining the System's Aspects of Interest and Measurable Produced Benefits

As the next step of the 6E framework, the system's *aspects of interest* should be defined. The stakeholder should determine with respect to what aspect the flexibility is measured. Some examples of these aspects for space systems are lifetime extension, expansion, dealing with partial failures or transformation of a mission to a new mission. If the stakeholder is concerned with flexibility in more than one aspect, *a set of aspects* can be defined for a system. For the purpose of flexibility calculation, the steps of the 6E framework can be repeated for each single aspect, or all aspects can be combined and then the framework applied.

The next important step is defining measurable *benefits* produced by the system within the chosen boundary. The concept of flexibility is associated with ease of change in value delivery of the system. A part of *value* is calculated from the system's *produced benefits*. The produced benefits should be measurable in order to be used in quantitative analysis of flexibility. The stakeholder determines the benefits of importance.

Figure 5.5. Examples of scientific satellites and space probes (clockwise from top left) Genesis, Galileo, Hubble Space Telescope (HST) and SOHO (Solar and Heliospheric Observatory), which produce non-monetary benefits.

A space system can produce monetary or non-monetary benefits. For most commercial space systems, the benefits produced can be measured in monetary value. In contrast, scientific space missions' benefits may be measured in data rate, number of images produced, the amount of measured data, etc., which are not usually measured in monetary value. For most types of non-monetary benefits, we are faced with the difficulty of finding a monetary equivalent, and much of the actual value may be lost during the process of converting the non-monetary benefits to monetary values. Some space systems have defined measures of benefits such as the Hubble Space Telescope. Hubble Space Telescope is designed for scientific exploration and the quality and quantity of the produced information is measured in a utility form defined by its users. The utility of the Hubble mission is measured by the *"discovery efficiency"* of the on-board payload instruments. Since designing flexibility into a system is usually associated with extra cost, the lack of a clear measure of its benefits can impede its implementation. Hence, the step of defining benefits of the system has a great importance in our framework.

5.1.3 Identifying Relevant Sources of Uncertainties

Depending on the flexibility aspect of importance, different related types of uncertainties can be recognized in a system. Recognizing related types of uncertainties has a critical role in measurements of flexibility in a system, since we can determine how well the uncertainties of importance can be modeled. In space systems, uncertainties may be related to technological innovations, lack of sufficient knowledge about the system or its environment, failure of a part or subsystem, market related uncertainty, or emergent behavior of the system.

Table 5.1 shows a set of aspects of interest to the stakeholder and the possible relevant uncertainties. For most of the mission, the likelihood of the part or subsystem failure is of importance and the way that we deal with partial failures is to embed redundancies in the system. For commercial missions and decisions related to expansion of the system or reengineering the system to perform a new function, market uncertainty plays an important role. For scientific missions, uncertainties associated with use of new technologies or new environments may be of more importance.

Table 5.1. A sample of space systems, aspects of interest, and the relevant uncertainties.

System Boundary	Aspect	Type of Uncertainty
Single commercial satellite	Lifetime extension	Market uncertainty Parts failure
Satellite cluster	Expansion	Market uncertainty
Single scientific satellite	Failure recovery	Parts failure Existence of servicing mission
Single commercial satellite	Transformation to a new future function	Market uncertainty

Each type of uncertainty may also be associated with one or more types of evaluation method. For example, if the space system of interest generates benefit or revenue which has a market history and we care about dealing with market uncertainties, the real option analysis may be a fitting approach to modeling uncertainty. For a scientific satellite system which does not generate any tradable commodity and uses unique technology with no history and background, decision analysis may be a more appropriate model of evaluation.

5.1.4 Choosing an Evaluation Methodology

Depending on the type of uncertainty, many different economic evaluation techniques are available. The choice of evaluation method depends on how well the methodology can capture a specific type of uncertainty in a system.

We divide different evaluation methodologies into three categories. The first category contains the methods that *do not* capture the uncertainty of the future. As an example of such methods, Discounted Cash Flow/Net Present Value can be mentioned. Discounted Cash Flow (DCF) as a financial tool does not have any means to capture the value of flexibility and cannot accommodate uncertainty in the future of the system. But currently it is a widespread tool used in many companies for decision making.

The second category includes the methods which capture the *technical uncertainties* and risks of a system. In situations where no market-related data exist, expert judgment is appropriate. We choose the decision analysis techniques for space systems with such embedded uncertainties.

In the third category, methods that deal with *market uncertainties* exist. Financial option pricing theory is the hallmark of this category. This theory uses the volatility of the market to reflect on the uncertainties of the values of the products or their sales. If the uncertainty of the system has a root in market uncertainty and data on the previous price of the system exist, this methodology is the most suitable one.

Here, we discuss three evaluation method categories that could be used in this step.

a) Discounted Cash Flow/Net Present Value

Net Present Value (NPV) is the most frequently used financial tool. It adjusts the future cash flow to the current dollar through using a discount rate. NPV methodology assumes a fixed scenario of starting and completing a project without any contingencies. The NPV formula is as follows:

$$NPV = \sum_{i=1}^{N} \frac{C_i}{(1+r)^i} \qquad (5.1)$$

where C_i is the cash flow in period i, r is the discount rate and N is the total number of periods.

Selecting a proper *discount rate* has a vital importance in NPV calculations. A low discount rate gives more weight to near-term cash flows, while a high discount rate gives distant cash flow much less weight and hence makes the project myopic in evaluation of potential future investments. The discount rate of a project depends on the possible opportunities for the project and is not a precise measure. There are different methodologies for capturing the value of the discount rate. One major method is Weighted Average Cost of Capital (WACC). WACC is an aggregate measure of average cost of money and estimated returns expected by investors. However, it does not reflect opportunity costs and there is no accounting for risk in the project. A better approach to adjusting the discount rate for uncertainty is the Capital Asset Pricing Model (CAPM). CAPM takes into account the investor's view of risk in investment and diversifies the variability in return through a collection of projects or a portfolio. Through the CAPM process, a risk-adjusted discount rate can be determined.

Three major downsides of this financial tool are a deterministic view of the future of a system (not considering the uncertainty and possibility for flexibility in a system), ignoring managerial flexibility, and subjective choice of discount rate. The issue of management's flexibility is of particular importance, since this approach cannot adapt and revise later decisions in response to unexpected market developments or technological uncertainties.

Traditional NPV makes implicit assumptions concerning an *"expected scenario"* of cash flows. NPV assumes passive management and commitment to a certain operation strategy, yet in the actual marketplace, which is characterized by change, uncertainty, and competitive advantage, there is a high probability of change of strategy from the initially planned one (Schwartz 2001).

Discounted Cash Flow (DCF) has the same problems as NPV, likewise assuming a passive investor. This method does not let any strategic decision in the future being captured, based on future information or events. However, an *"expanded NPV"* has been developed in order to incorporate management flexibility into traditional method. Expanded NPV is defined as follows:

Expanded (strategic) NPV = Static (passive) NPV of expected cash flows + value of options[16] from active management. (5.2)

The concept of options and specifically real options will be discussed later in this chapter.

b) Decision Analysis

Decision Analysis is a simple standard method for defining a wide range of choices over several periods. A decision tree is a representation of decision analysis which includes choices, uncertainties, possible outcomes, and the value of each possible outcome. Decision-Tree Analysis (DTA) is a useful tool in analysis of sequential complex decisions, but the representation of uncertainty is discrete in time. DTA includes management flexibility and recognizes the interdependencies between initial and subsequent decisions. An optimal decision is calculated by starting at the end of the tree, calculating the expected value of the alternatives, and working backwards in the decision tree.

Decision Analysis is very useful in situations where:

- Likelihood and timing of uncertainties are understood
- Information source focuses on individual projects
- Important variables do not have a price history (de Neufville 2004).

An example of decision analysis adopted from Saleh (2002) on on-orbit servicing is presented in Figure 5.6. Let us assume that a satellite is designed to be serviceable, and the initial design lifetime is 10 years. Currently, the satellite is operating in its 9th year of operation and we are faced with the decision of servicing the satellite for a life extension of two more years. If we assume that the current revenue of the satellite is S_0 (revenue per day), we recognize that, a year from now, the revenue may go up or down, which is shown by S_{up} and S_{down}. The cost of servicing and operations are assumed to be $C_{service}$ and C_{op}. Δt is the duration of life extension in days. At year 10 of operation we are faced with a decision about servicing the satellite. If the revenue per day increases in the future,

---

[16] "An option is the capability or right to take some action, without the obligation to do so" (De Neufville 2002).

$S_{up} \succ \dfrac{C_{service} + C_{op} \cdot \Delta t}{\Delta t}$, the payoffs from servicing or not servicing the satellite are shown in the right hand side of the tree. If the revenue per day goes down in year 10, or $S_{down} \prec \dfrac{C_{service} + C_{op} \cdot \Delta t}{\Delta t}$, the payoffs of performing or not performing the servicing mission can also be calculated. The expected value of the tree with an embedded servicing option is calculated as follows:

$$EV_{Servicing} = p \cdot \left(\frac{(S_{up} - C_{op})\Delta t - C_{service}}{1+r} \right) + (1-p) \times 0 \qquad (5.3)$$

where r is the discount rate.

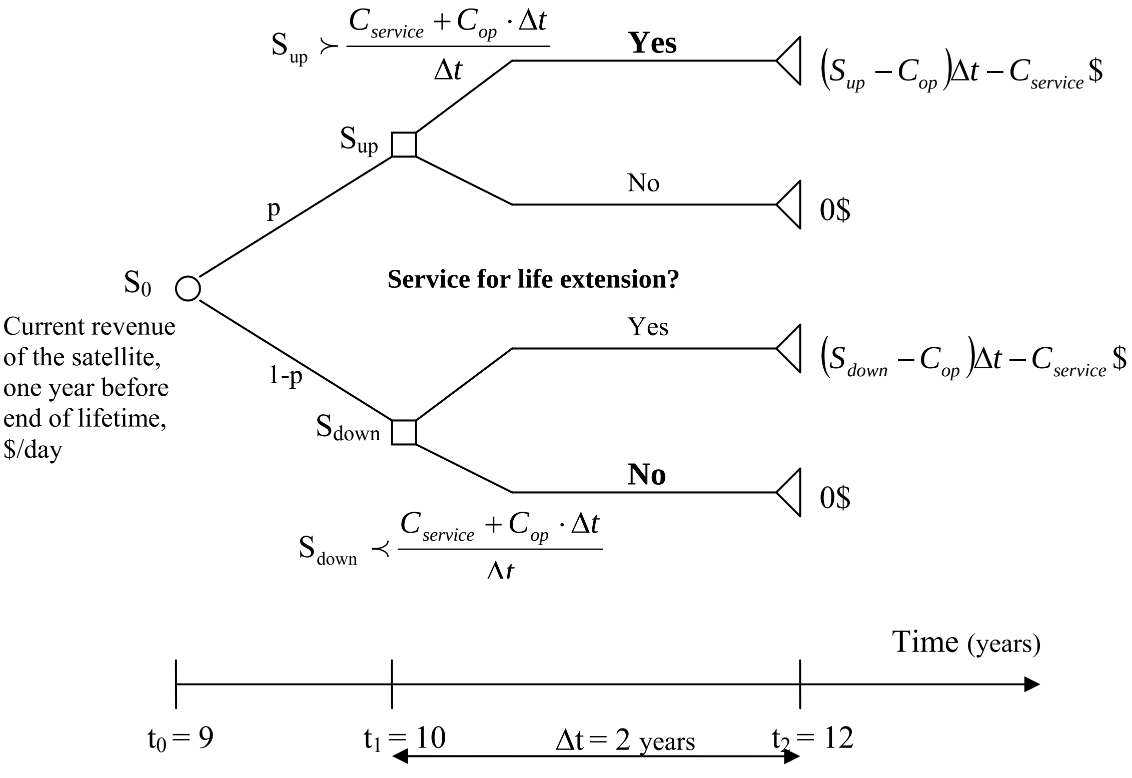


Figure 5.6. A simple decision tree for servicing a satellite (adopted and modified from Saleh, 2000)

There are some limitations to Decision-Tree Analysis. When applied to real cases with several decision and chance nodes, DTA becomes unmanageable and the tree expands geometrically with the number of decision nodes. The other limitation originates from the discrete characterization of uncertainty which is used in a DTA. This methodology cannot be used for uncertainties of a continuous nature. There is also the subjective choice of discount rate in calculation of the expected value of the tree.

c) Option Analysis

What is an option?

Option analysis is a way of defining flexibility in a system. “An option is the capability or right to take some action, without the obligation to do so” (De Neufville 2002). The option concept has revolutionized the academic’s and the practitioner’s approach to project investment and is also capable of incorporating management flexibility into the analysis. The option concept is based on *asymmetric returns*, and an option is exercised only when advantageous. The first options and relevant evaluation techniques were created in the field of finance. Financial options are tradable assets which are sold through exchanges for all kinds of stocks, commodities and foreign exchange (De Neufville 2004).

There are two major types of financial options, call and put options. A *call option* is the right to acquire an asset at some future time for a known cost (a set price). A *put option* is the right to sell an asset in the future for a known price, no matter what the market price in the future will be. It creates the right to limit the losses of an undesirable situation.

There are several important variables and concepts in options which are discussed briefly below.

> *Underlying asset:* The asset which the real option gives us the right to buy or sell (Howell 2001)
>
> *Strike price:* A known price at which a call or put option allows us to buy or sell a given asset.
>
> *Fluctuating market price S:* Fluctuating market price of an underlying asset.
>
> *Payoff:* Net gained value from having an option.

Let us consider an example of a call option. Assume a call option gives a stakeholder the right to buy an asset for a predetermined strike price, K. The only rational time for the exercise of the option is when the asset price is greater than the strike price or S>K. If the option is exercised, the payoff is S^*-K, where S^* is S at the moment of exercise. If the option is not exercised, the payoff is zero or, in general, $Payoff = Max[0, S^* - K]$. The value of an option, however, differs from the payoff. The value of an option is the maximum value of exercising the option now and exercising it in the future (de Neufville 2004). Figure 5.7 presents the *at the money* option on a project. If the option is exercised immediately, the payoff will be zero. But based on the Probability Distribution Function (PDF), there is a probability distribution that the asset will have a higher expected value than zero. Here the concepts of *volatility* and *time to expiration* of an option play an important role.

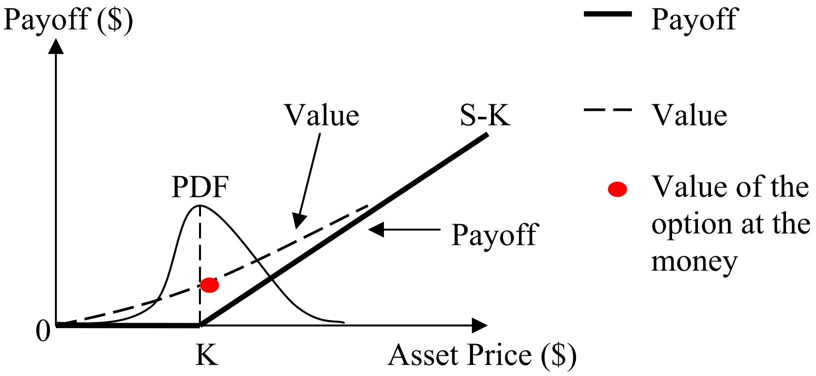


Figure 5.7. An option *at the money*. The immediate payoff is zero, but the value of the option is not (adopted from de Neufville 2004).

Volatility is the speed at which the market value of the underlying asset tends to diverge randomly from its current value as time passes by. In other word, volatility is the tendency of the market value of the underlying asset to diffuse over time away from its present value (Howell 2001). Higher volatility indicates larger speed of divergence and larger possible upside and downside variations. In Figure 5.7, higher volatility would be associated with wider PDF and therefore a higher option value. It should be noted that options have an *expiration date*, which is the date that an option to invest or sell ends. Options with higher remaining time to expiration, have more value than ones with a shorter time to expiration.

Real options refers to options on *projects and systems,* in contrast to financial options that are *contracts*. There are two major types of real options, which are defined as follows:

> *Call-like option:* It captures the benefits which are the result of increase in value of the project. This type of option is usually exercised when probability of positive return is high, and its exercise usually involves spending money on the project. It creates the right to take advantage of an opportunity. Some examples of call-like options are waiting to invest, expanding, and restarting a closed operation.
>
> *Put-like option:* This type of real option acts as an insurance against losses if the value of the project decreases. A put-like real option may be exercised when we expect losses in the system, and it usually involves short-term costs or salvage value. Some examples of put-like options are abandonment, reducing, and temporary shut-down of the operations.

Real options can be applied **in** or **on** a project or a system. Real options **in** a system are concerned with applying options through technical modification, change in design of projects and systems. The creator of such an option should have a good knowledge of the technical system or project of interest. Real options **on** a system are similar to financial options, but they are on technical projects or systems. Real options on a project treat the system or project as a black box, and no detailed technical knowledge of the system is necessary (de Neufville 2004).

Valuation of a real option

The option pricing theory was developed by Black and Scholes (1973), Merton (1973), and Cox and Ross (1976). It introduces the concept of pricing securities by arbitrage method. The real options analysis is based on the option pricing theory which assumes that each value driving factor follows an unforecastable *random walk*. In any instance, likelihood of upward or downward movement of the value of the underlying asset is the same. An option is valued relative to the underlying asset, and it has the same value as the *risk-neutral* environment. Then, in option calculations, *a risk-free rate of return* is being used (Schwartz et al. 2001). The use of a risk-neutral framework has the following benefits:

- It accounts for all possible options that a project or system may have.
- It can use all the information in market prices when such prices exist.
- It allows using the analytical tools to determine the value of investment in the project and optimal operating policy.

In practice, most of the real option problems must be solved through *numerical methods*, in many cases modeled using partial differential equations (PDEs) and *appropriate boundary conditions* that the value of the project should satisfy. The benefits of numerical methods come in determining an optimal strategy as well as value for flexibility in a project. The easiest method involves two state variables which are solved through binomial lattice analysis. If the problem involves more state variables or is path-dependent, Monte Carlo simulation is a better practical choice.

Option analysis is a suitable choice where extensive data exist on the price of the asset and its standard deviation. The analysis assumes that no decision that is taken will change the future course of a random walk. Here, we briefly introduce some of the above-mentioned methods.

1) Binomial Lattice Analysis: Binomial lattice analysis is based on a sequence of possible binary outcomes, which are branching forward from the present (Howell 2001). At each step, the branch doubles. The most common type of binomial trees is recombining lattice. Recombining removes the curse of dimensionality and the number of states increases linearly with the number of periods. A binomial lattice model assumes a stationary evolution process over time and each state leads to up and down states over a period of time. The model also assumes path independency, which make us more cautious about using it with *real systems and projects*. If the beginning state is *S*, after a period, there are two states of *uS* and *dS* which are the *up* and *down states*. Figure 5.8 shows a binomial tree, with different states and probabilities in each state. The following relationships are used to calculate probability *p, u,* and *d* based on volatility and length of tree period, Δt.

$$u = e^{\sigma\sqrt{\Delta t}}$$

$$d = e^{-\sigma\sqrt{\Delta t}}$$

$$p = 0.5 + 0.5(\upsilon/\sigma)\sqrt{\Delta t} \qquad (5.4)$$

where σ is the market volatility, υ is the average price increase, and u and d are the values of up and down which are multiplied in original S to yield the value of S after a period.

It should be noted that after some number of periods, a probability distribution function for lattice outcomes can be observed. An example of such a PDF can be seen in Figure 5.9. The binomial PDF results have *log-normal distribution*.

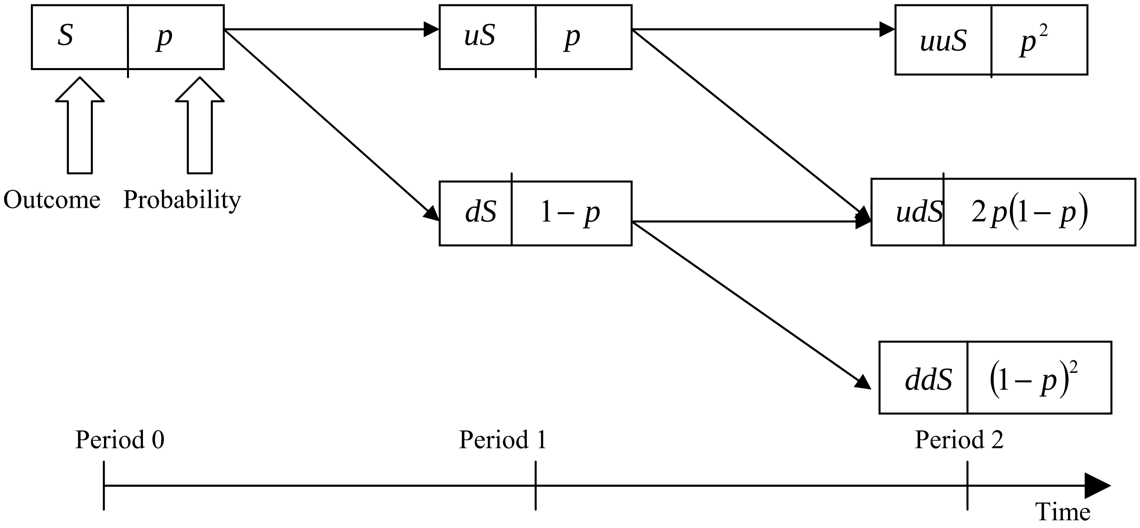


Figure 5.8. A schematic of a binomial lattice of outcomes and probabilities for two periods (adapted from de Neufville, 2004)

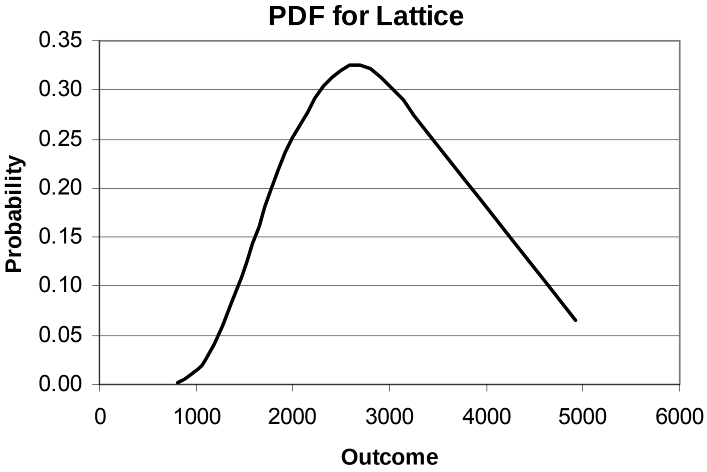


Figure 5.9. An example of a probability distribution function for outcomes after *n* periods.

The valuation methodology of a binomial tree is very similar to the decision-tree analysis. First, all possible states over all periods with their associated probabilities are determined. Then, working from the last period backward, we calculate the expected value of the best choice, and then use the dynamic programming technique to roll back the results to the beginning of the tree. For a more detailed in-depth analysis of binomial lattice analysis, the reader is referred to Schwartz and Trigeorgis (2001).

Black-Scholes Equation: In 1973, Fischer Black and Myron Scholes published their groundbreaking paper "The pricing of options and corporate liabilities"(Black and Scholes 1973). This paper contained the first successful options pricing formula and described a general framework for pricing other derivative instruments. Black, Scholes, and Merton won the 1997 Nobel Prize in economics for their contribution in financial option theory.

The *Black-Scholes equation* is based on the random walk or geometric Brownian motion. This partial differential equation relates the rate of change in the value of the derivative to time and to the random variables which are presently observable, without the need to acquire knowledge of the next change in the random variable(s) (Howell 2001). The Black-Scholes equation can have different forms, depending on the number of independent random factors and several boundary conditions. In order to achieve *a unique solution* to the Black-Scholes equation, *boundary conditions* should be applied to the equation. The classic form of the Black-Scholes partial differential equation is presented as follows:

$$rV = r\left(\frac{\partial V}{\partial S}\right)S + \frac{\partial V}{\partial t} + 0.5S^2\sigma^2\left(\frac{\partial^2 V}{\partial S^2}\right) \tag{5.5}$$

where *V* is for asset value, *S* is the current price of the underlying asset, σ as the volatility of the asset price, and *r* as the risk-free rate of return.

The Black-Scholes *formula* is a unique solution to the Black-Scholes equation. The equation is solved subject to meeting the boundary conditions, which for the option should be a European call with one-time exercise only on a non-dividend-paying asset. The closed-form formula is presented as follows:

$$V_{OPTION} = S \times N(d_1) - Ke^{-rt} \times N(d_2) \tag{5.6}$$

where

$$\begin{aligned} N(x) &= \int \frac{1}{\sqrt{2\pi}} e^{-y^2} dy \\ d_1 &= \frac{\left\lfloor \ln(S/K) + \left(r + \sigma^2/2\right) \times t \right\rfloor}{\sigma\sqrt{t}} \\ d_2 &= d_1 - \sigma\sqrt{t} \end{aligned} \tag{5.7}$$

N = normal distribution function
S = current price of the asset
K = strike price of the asset
r = risk-free rate of return
t = time to expiration
σ = volatility of the share price per period

The Black-Scholes equation has been used previously in the field of space systems by Saleh (2002). He derives and modifies the formula to apply it to the problem of evaluation of on-orbit servicing. He considers servicing of the satellites as a one-time exercise call option and calculates the value of this option, gained through on-orbit servicing, for the customer or stakeholder of the satellite. The reader is recommended to refer to his thesis (Saleh 2002) on the issue for further study of the subject.

Simulation: Monte Carlo simulation is a method that simulates the behavior of a stochastic system by drawing a large number of random trials of the stochastic behavior. A Monte Carlo simulation can use sequences of random numbers as the basis for uncertainty in the calculations, and it is named in reference to a gambling casino. An option value is calculated for each walk by discounting back from the value at expiry and the current option value is estimated as the average of a large number of these simulations. The major advantage of the Monte Carlo simulation is in directness and clarity of the method. The method is very useful when the value of the option is simultaneously dependent on the price of several underlying assets.

Evaluation Methods in a Nutshell

In the previous section, we discussed a sample of well-known and frequently used evaluation methods. The goal of introducing these methods is to find the most suitable method or combination of methods which maps to the uncertainty at hand. Depending on the type of uncertainties, a single evaluation method or a combination of methods can be used. Figure 5.10 shows a high-level view of the evaluation methods and their relationships to the market or project-specific uncertainties (Adapted from Neely, 1998).

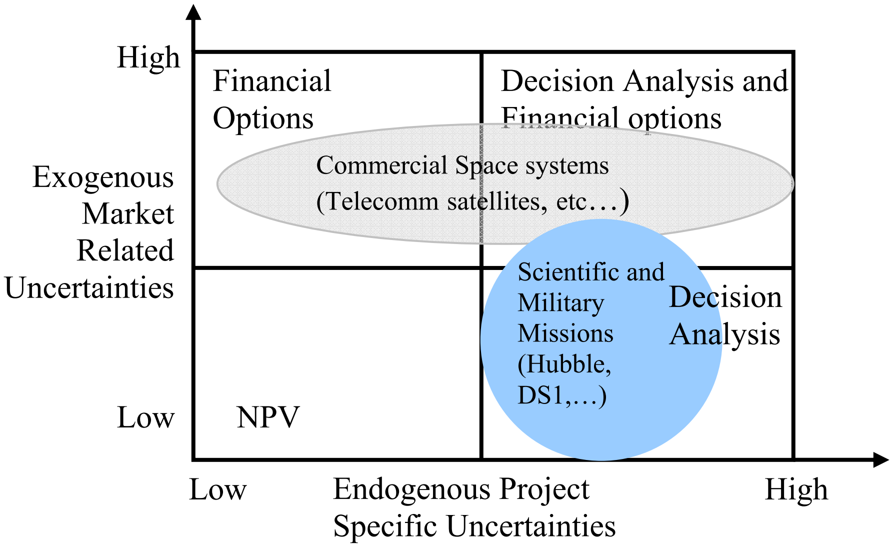


Figure 5.10. Choice of methods and the categories of space systems. (adapted from Neely 1998[17]).

As can be seen in Figure 5.10, the NPV is a suitable method of evaluation when there is *very low* market or technological uncertainty. If the source of uncertainty of concern is the market, option theory provides a suitable framework for modeling and evaluation of the expected benefits and costs associated with different alternatives to implement flexibility in the system. For example, if we are concerned with having flexibility with respect to market uncertainty in a telecommunication satellite, real options is an appropriate evaluation method. If the source of uncertainty is *project-specific* or non-market-related, decision analysis can be an appropriate method. Examples of such systems are the Hubble

---

[17] Improving the valuation of research and development : a composite of real options, decision analysis and benefit valuation frameworks , James Edwin Neely, 1998

space telescope and other deep space probes. These missions usually have a scientific objective, which is not driven by the market. In cases where the source of uncertainty is both driven by the market and also technology- and project-specific uncertainty, a *hybrid* of real options and decision analysis may be used. Many commercial satellites can be classified in this domain, depending on the flexibility aspect of interest. The reader is referred to de Neufville and Neely's paper (2001)[18] on hybrid method for further study on the subject.

Modeling of Uncertainty	None	CAPM	Hybrid	Replicating Portfolio
Simulation				
Non-recombinant lattice				
GBM				Black-Scholes
Lattice				Binomial Lattice
Subjective Probabilities		Decision Analysis	Neely's Method	
None	DCF			

Valuation of Uncertainty

Figure 5.11. Different methods and models of valuation of options under uncertainty. Adapted from de Neufville lectures, 2005.

Figure 5.11 shows the different models of uncertainty and their approach to valuating uncertainty in a system.

---

[18] Hybrid Real Options Valuation of Risky Product Development Projects, Richard de Neufville and James Neely - International Journal of Technology, Policy and Management, Vol.1, No.1, pp.29-46, Jan. 2001

5.1.5 Choosing a Baseline and Developing Alternatives

At this stage in the framework, we need several alternatives that can introduce flexibility into our specific chosen system, and a baseline case as an anchor to which *compare* the alternatives. We define the baseline and alternatives as follows:

- *A baseline* is a space system or a space system architecture which is designed and operated in a traditional way. We can say that the architecture was not designed specifically to deal with future technological or market uncertainties in mind. There is also the assumption that flexibility was not intentionally embedded in the architecture, either in the design phase or as a strategic decision during the architecture's operation. It should be noted that risk and probability of failure are usually thought about in the design phase of a space system and most of these baseline or traditional designs have redundancies which create robustness in the system in face of partial failures.
- *Alternatives* are a set of architectures which contain flexibility. An alternative can be an architecture which has flexibility embedded in it in a specific manner and amount in the initial design phase. It can also be a set of strategic decisions and modifications to the system after the system is deployed. A hybrid of design modification and future decisions and changes can also create an alternative. It should be noted that each alternative should be identified clearly and should be compatible with the degree of access which was discussed in chapter 4. The degree of access defines whether the suggested solution is feasible or not. For example, in case of interplanetary space probes, an alternative which includes implementing flexibility through physical manipulation of the system may not be possible.

Here we present an example of a baseline and several alternatives. Imagine we are in design phase, with the goal of designing a new GEO satellite. The time window of interest is 10 years since the start of operation of the satellite. If the most important uncertainty is technological uncertainty (change and/or substantial improvement of the technology over the chosen period of time), the alternatives are set up in a way to deal with this existing uncertainty. Some suggested alternatives can be seen in Figure 5.12. The baseline is defined as a traditional GEO satellite design, which will work over a period of 10 years and will retire after that period. The baseline satellite does not have any built-in capability for modification, on orbit servicing, or other options.

The first alternative considered is building a GEO satellite with 5 years of lifetime, and launching a similar satellite, but with updated technology, after 5 years. The second alternative suggested is to modify the original satellite to be serviceable. Later, half-way through its lifetime, a servicing mission can be performed and the specific technology can be upgraded. The third alternative is the original satellite design, plus at year 5 flybying the particular new technology (if possible) without intrusive servicing.

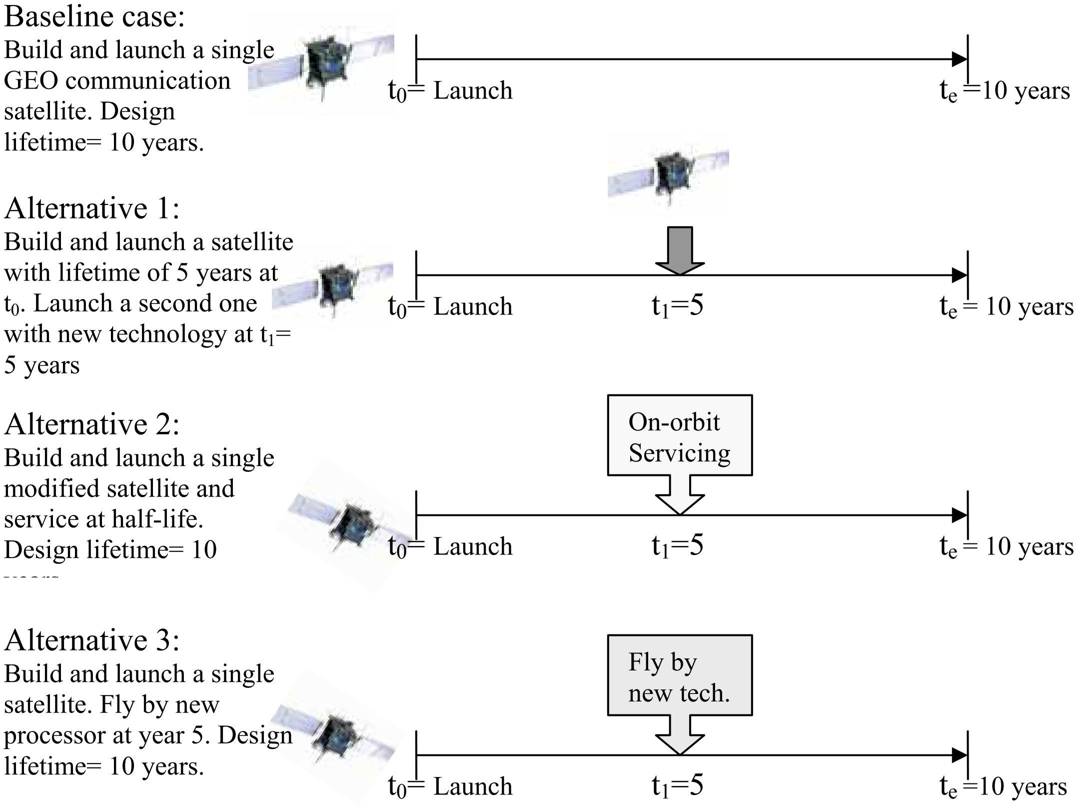


Figure 5.12. A demonstration of a baseline and three alternatives for the case of lifetime extension of a GEO telecommunication satellite.

The possible alternatives that match the level of access to the system are numerous. One can create several alternatives and measure the value of flexibility each alternative can create in the system with comparison to the base case. Some of these alternatives can be created through change in technical design of a space system, which may be treated as options **in** the system. Other alternative can also be created through a set of strategies and decisions **on** a space system.

5.1.6 Applying Evaluation Methods to Baseline and Alternatives

At this stage, we apply the chosen economic evaluation method to the baseline and each of the alternatives separately. The cumulative costs and benefits of the system should be calculated separately. Calculating the cumulative costs and benefits of the baseline is usually straightforward. However, calculating the expected[19] costs and benefits for each alternative is more complicated, since a considerable change in the original design may be required. If an alternative necessitates modification in the original design, then the new expected costs and benefits associated with the new design are calculated. If there is no modification necessary in the original design, the expected costs and benefits of changes or modifications associated with strategic decisions are calculated and added to the baseline expected costs and benefits.

We present the expected benefits and costs of a system in a vector form. The baseline and each alternative can be shown in a $1 \times n + 1$ vector containing different types of benefits and total costs of the alternative. Expected costs of baseline and each alternative are usually in monetary units and can be added and represented as an element of EC in the vector. Different types of benefits include a set of monetary and/or non-monetary benefits. Each type has a different unit such as dollars, # of images taken, size of the scientific data transferred, etc. which cannot be added together. It should be noted that benefits of the same type can be *added* together, such as multiple sources of income from a satellite, which can be measured and added as dollars.

---

[19] Definition of the expected value: if *s* is a random event with possible outcomes s_1, s_s, …, s_n for *n* outcomes with probabilities $p_1, p_2, \ldots, p_n$ such that $p_1 + p_2 + \ldots + p_n = 1$, then the expected value of *s*, is given by

$$E[s] = p_1 s_1 + p_2 s_2 + \ldots + p_n s_n$$

In order to build such vectors we start with a set of different types of expected benefits for baseline and each alternative. Imagine we have *m* sets from $A_1 \ldots A_m$. The union of different expected benefit types ($\bigcup_{i=1}^{m} A_i$) determines *n*, which is the number of expected benefits in the system. The EBC (Expected Benefits and Costs) vector then becomes a $1 \times n+1$ vector.

The vectors for baseline and alternatives are defined as follows:
Baseline case expected benefits-costs vector = $Base = (EB_{b1},...,EB_{bn},EC_b)$
Alternative *x* expected benefits-costs vector = $Alt_x = (EB_{x1},...,EB_{xn},EC_x)$
where b and x stand for baseline and alternative x, $EB_{b1},...,EB_{bn}$ are *n* different types of expected benefits produced by the baseline system over the designated timeframe, and $EB_{x1},...,EB_{xn}$ are *n* different types of expected benefits by alternative case *x*. EC_b and EC_x show the expected cost of baseline and alternative *x*, respectively.

The next step in the framework is calculating the differences of the expected costs and benefits of alternatives from the baseline. This can be shown as follows:

$$\Delta EBC_x = Alt_x - Base = (EB_{x1},...,EB_{xn},EC_x) - (EB_{b1},...,EB_{bn},EC_b)$$

$$\Delta EBC_x = (EB_{x1} - EB_{b1},...,EB_{xn} - EB_{bn},EC_x - EC_b)$$

or

$$\Delta EBC_x = (\Delta EB_{x1},...,\Delta EB_{xn},\Delta EC_x) \qquad (5.8)$$

The ΔEBC_x vector creates a base for performing a trade-off between extra cost and additional total gained benefits of a system. If the only produced benefit of a space system is measured in monetary units, we have a 1 by 2 vector, in which the first element shows the extra dollar benefit gained through alternative x, and the second element shows the extra cost spent to get the extra benefit through alternative x.

We present an example to illustrate on the problem of multiple variable non-monetary benefits. Let us consider satellite TERRA by NASA. TERRA is an Earth-observing satellite with 15 years of lifetime, which has five major instruments on board. For simplification, we consider an option to upgrade the satellite after 5 years of operation, which affects three instruments' performance, and produced benefits respectively. The three instruments which create measurable benefits are:

Instrument 1= ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer

Instrument 2= CERES: Clouds and the Earth's Radiant Energy System

Instrument 3= MISR: Multi-angle Imaging Spectro-Radiometer

We assume that each of these instruments generates data and their benefits can be measured and quantified.

Base Case: Current TERRA satellite
Lifetime= 15 years
Expected benefits of instrument 1 (ASTER) = EB_{Base1}
Expected benefits of instrument 2 (CERES) = EB_{Base2}
Expected benefits of instrument 3 (MISR) = EB_{Base3}
Expected cost of mission = EC_{Base}

Flexible option X: Upgrade satellite in year 5 of operation
Lifetime= 15 years
Expected benefits of instrument 1 (ASTER) = EB_{X1}
Expected benefits of instrument 2 (CERES) = EB_{X2}
Expected benefits of instrument 3 (MISR) = EB_{X3}
Expected cost of mission = EC_X

Figure 5.13. TERRA satellite base case and an option to upgrade

The baseline case expected benefits and costs vector is presented as

$$Base = \left(EB_{Base1}, EB_{Base2}, EB_{Base3}, EC_{Base}\right)$$

and the same vector for alternative *x* is presented as

$$Alt_x = (EB_{x1}, EB_{x2}, EB_{x3}, EC_x)$$

The ΔEBC_x vector is calculated to be as follows:

$$\Delta EBC_x = (\Delta EB_{x1}, \Delta EB_{x2}, \Delta EB_{x3}, \Delta EC_x)$$

where ΔEBC_x show the different types of extra benefits and the associated cost of choosing the alternative *x*.

5.1.7 Non-monetary Benefits and Prospect Theory (optional)

This step of the framework is completely optional. We can proceed to create a tradespace based on the ΔEBC_x vector in the next step of the framework. A more accurate way of capturing the real value of extra benefits to the stakeholder is taking advantage of *Prospect theory*. In this section, a brief review of utility theory and its shortcomings for capturing the changing value is presented. A brief description of prospect theory is then presented. (The extended application of prospect theory in space systems must be left for future work.)

The psychological approach to decision theory is traced back historically to an essay by Daniel Bernoulli published in 1738. He suggested that people evaluate prospect by *expected subjective value of the outcomes*. He proposed a subjective value or utility as a concave function on money. Expected utility theory begins from his time. Utility is one of the basic ways of representing non-linear preferences for possible benefits and losses. Utility functions are the result of a set of assumptions and are applied to situations involving uncertainty. They are routinely used in decision analysis and are based on rational choice (Keeney and Raifa 1993).

The utility function $U(x)$ is a type of value function whose units have meaning relative to each other. The utility function exists in a particular cardinal scale on which values can be calculated meaningfully. The scale of utility is an ordered metric scale. In this scale the units are constant, identifiable amounts which can be combined linearly by addition, subtraction, or averaging. But zero on an ordered metric scale has no absolute meaning; it acts just as a reference point. Measurements of utility on an ordered metric scale can be transformed into equivalents by a positive linear transformation:

$$U'(X) = aU(X) \pm b \tag{5.9}$$

where $U'(X)$ and $U(X)$ are strategically equivalent (de Neufville 1990). Traditionally, in calculations of utility, a dimensionless scale from zero to one is used. The utility is considered zero for the least desirable acceptable level and is defined as one for the highest desirable level. Some typical forms of utility functions can be seen in Figure 5.14.

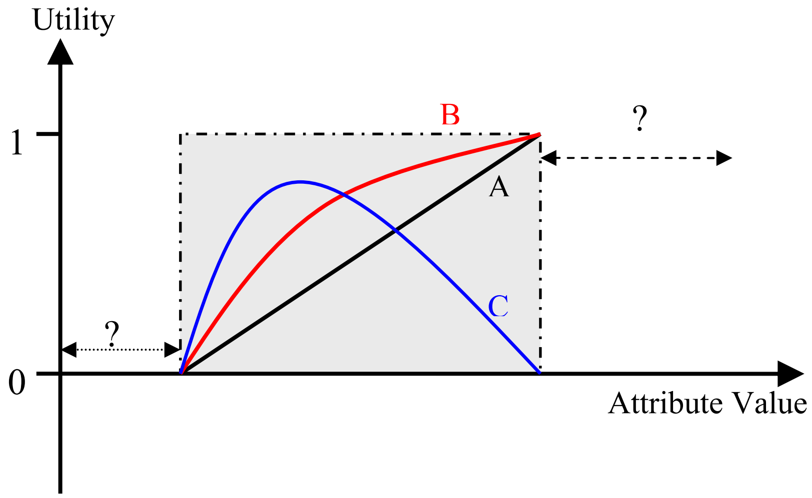


Figure 5.14. Some different types of utility function (A: linear, B: diminishing returns, C: non-monotonic). The utilities less than zero and more than one are usually not determined. (Adapted from SSPARC)

In calculation of utility, utilities over one or less than zero are usually ignored. As can be seen in the gray box of Figure 5.14, utility theory is only concerned with the *current* range of zero to one of the utility. The boundaries of the box change with time, because the range of desirability of an attribute may change with time. For example, the memory range of a commercial integrated circuit changes every 9 months and its utility today is considered out of the range of utility of the system a year before. In calculating flexibility of a space system, we are concerned with *change from the current status quo*, and utility theory only results in status quo preferences. It cannot capture the value of changing benefits. This is one of the shortcomings of utility theory. The current processes are based on meeting *static requirements* and there is no reward for “extra” performance at all, even if there are potential benefits to the user (Ross et al. 2004). Negative values of utility are by definition excluded, but sometimes are required in calculation of flexibility. In systems with multiple generated benefits, a stakeholder may *sacrifice* a certain benefit to obtain a higher gain on the other benefits. It also fails to capture the extra benefits beyond status quo benefits. It also assumes the user’s preference must be *linear with probability* within the bounds of the problem.

A better way of capturing user preference on the matter of flexibility is *Prospect theory*, which was founded by Kahneman and Tversky (1979). Markowitz (1952) was the first to propose that utility is better defined as gains and losses rather than final asset position. In prospect theory, the carriers of utility are not *states* (e.g., owning or not owning a property), but *changes in the states*. The central assumption of prospect theory is a gain and loss view rather than a total asset view. The topical organization of mental accounts also leads a stakeholder to evaluate relative gains and losses rather than absolute asset values (Kahneman 2000).

When value functions for gain and loss are merged together, they create an S-shaped function which can be seen in Figure 5.15. The characteristics of such a value function are:

- It is defined by gains and losses rather than the total value.
- It is concave in the domain of gain and convex in the domain of losses.
- It is considerably steeper for losses than for gains. This characteristic is related to the concept of loss aversion.

Loss aversion means that loss of $X is more aversive than a gain of $X is attractive. Loss aversion is shown by people’s reluctance to bet on a fair coin for equal stakes. It also proposes that risk-seeking behavior in the domain of losses exists. It has been observed that people are often risk-seeking in dealing with improbable gains and risk-averse in dealing with unlikely losses.

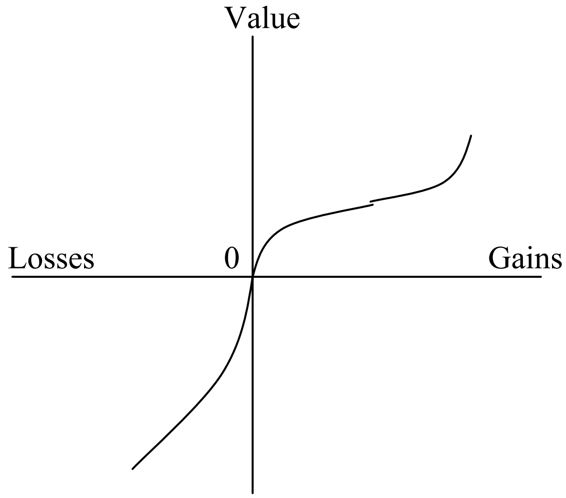


Figure 5.15. A hypothetical value function. (from Kahneman and Tversky 2000)

Prospect theory has two major sets of elements: value functions and decision weights. The value function $v(x)$ assigns a number to each outcome x that reflects the subjective value of that outcome. Outcomes are defined relative to a reference point, which is the zero of the value scale. A value function $v(x)$ measures *the value of deviation from the reference point* which is zero on the losses or gains scale. The value is usually a nonlinear probability of winning. Decision weight $\pi(p)$ is the weight associated with probability p . It should be noted that $\pi(p)$ is not a probability measure and typically $\pi(p)+\pi(1-p)\leq 1$. Figure 5.16 shows a hypothetical weighting function.

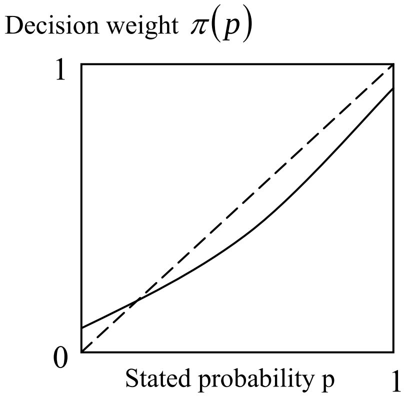


Figure 5.16. A hypothetical weighting function (from Kahneman and Tversky 2000)

Let us assume we have two non-zero outcomes of a lottery which are shown as $(x,p;y,q)$, where x has a probability p and y has a probability q. The overall value function V is calculated as follows:

1. In the case of a regular prospect, either $p+q \prec 1$, or $x \geq 0 \geq y$, or $x \leq 0 \leq y$, then
$$V(x,p;y,q)=\pi(p)v(x)+\pi(q)v(y) \tag{5.10}$$

2. In the case of a strictly positive or strictly negative prospect, $p+q=1$, $x \geq y \geq 0$, or $x \leq y \leq 0$, then
$$V(x,p;y,q)=v(y)+\pi(p)(v(x)-v(y)) \tag{5.11}$$

For both cases, $v(0)=0$, $\pi(0)=0$ and $\pi(1)=1$.

The equations of prospect theory retain the general bilinear form of underlying utility theory. Several different ways of capturing the weighting function exist. One suggestion is the following form gained from data fitting:

$$\pi^{+}(p)=\frac{p^{\gamma}}{\left(p^{\gamma}+(1-p)^{\gamma}\right)^{1/\gamma}} \qquad \text{weighting function for gains} \tag{5.12}$$

$$\pi^{-}(p)=\frac{p^{\delta}}{\left(p^{\delta}+(1-p)^{\delta}\right)^{1/\delta}} \qquad \text{weighting function for losses} \tag{5.13}$$

where

γ = Probability weighting parameter for gains

δ = Probability weighting parameter for losses

The value function is presented in the following form:

$$v(x)=\begin{cases} x^{\alpha} & if \quad x \geq 0 \\ -\lambda(-x)^{\beta} & if \quad x \prec 0 \end{cases} \tag{5.14}$$

where

α = Power for gains

β = Power for losses

λ = Loss aversion

Using prospect theory in the flexibility framework is optional. It is most useful when the value function attached to each produced benefit by an alternative is very nonlinear. In case of a linear preference for benefit in the region of study, the raw produced benefits of the system can be used to construct a flexibility tradespace.

5.1.8 Creating a Flexibility Tradespace

In this step, we can create a tradespace of delta cost vs. delta benefits (or prospect values). Each point in this tradespace shows the extra value gained through implementing an alternative vs. the associated cost. Each point shows an alternative or option for acquiring flexibility in a system. What we are seeking are designs or alternatives that have a lower delta cost with the highest prospect value. These alternatives are the most flexible alternatives, since they create the least resistance (delta cost) towards an upward move in value delivery (higher prospect value). Figure 5.17 shows what such a trade-space may look like.

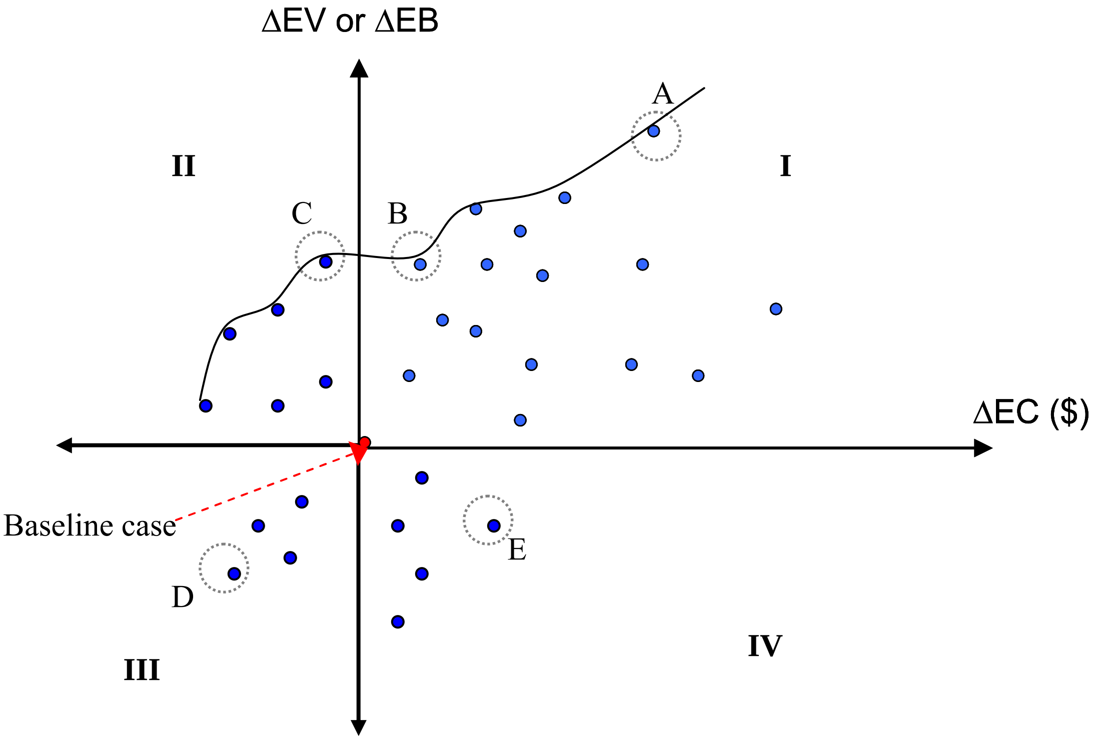


Figure 5.17. Hypothetical flexibility tradespace. The vertical axis is delta cost and the horizontal axis is delta benefits.

Each point in Figure 5.17 shows an alternative way or option with respect to baseline. The location of the chosen baseline case is on the zero of ΔEV or ΔEB, and ΔEC axes. The alternatives existing in the fourth quarter (IV) such as E are not flexible, because the benefits decreases through choosing the alternative, while the associated cost of implementing the alternative is larger than zero. The second and third quadrant (II and III) exist mostly in the design phase, because a system in operation is already associated with a certain cost, and every alternative way of implementing flexibility only adds to the original cost spent. An alternative in the first quadrant (I) is flexible relative to the baseline case, and the alternatives with lowest additional cost and the largest benefits are the most flexible options. A Pareto front may be observed if a large number of alternatives exist. Alternatives *A* and *B* are located on such a Pareto front.

5.2 Implementing the Flexibility Framework in the Design Phase

The design phase is one of the most important opportunities to create and implement flexibility in a space system. If the relevant uncertainty is recognized and the suitable solution is built into the space system in the design phase, it will usually cost less in comparison with a solution implemented in a space system after the space system has been fielded. The preliminary design phase is therefore a critical stage for implementing flexibility.

In this section, we will briefly review preliminary design phase methodologies. The Space Mission Analysis and Design (SMAD) preliminary design phase methodology is first presented. Next, the Generalized Information Network Analysis (GINA) is presented, and following that, a more complete form of GINA, Multi Attribute Tradespace Exploration (MATE). We find MATE in its current form unsuitable for use in a methodology to capture the value of flexibility in different architectures and designs. The sources of incompatibility are discussed. Then a reform in the current MATE methodology is suggested in order to merge the 6E flexibility framework with the MATE process. The result of this merger is presented as the FlexiMATE framework. Finally, the detailed methodology is presented.

Some definitions of frequently used terms

GINA: A generalized analysis methodology for satellite systems which can be used for the analysis of space system architectures with missions in communications, sensing, or navigation. The generalized information network analysis (GINA) methodology is a hybrid of information network flow analysis, signal and antenna theory, space systems engineering, and econometrics. The methodology specifies practical metrics for the cost, capability, performance, and adaptability of architectures (Shaw 2001). It standardizes the representation of the overall mission objective, in terms of a generalized quality of service parameter. GINA includes the system modeling and trade space exploration aspects of MATE (see below) without the front-end of a generalized multi-attribute utility method. This methodology is specialized for systems that are primarily focused on information transfer, but has been used generally in a similar fashion to MATE.

MATE: The Multi-Attribute Tradespace Exploration (MATE) is a model-based high-level assessment of many possible solutions to the problem to be considered (Ross et al. 2004).

Multi-Attribute Utility theory

"A multi-attribute utility combines single attribute utilities into a combined metric that can be used to rank user preferences for any set of possible values of the attributes" (Ross et al. 2004).

5.2.1 MATE Process and Its Origins

The idea of MATE process in space systems was created in the face of the inefficient and limited design methodologies of the time. One of the most important of these is the preliminary design methodology presented in Space Mission Analysis and Design (SMAD 1999). The SMAD process contains the following steps:

a. Define broad objectives and constraints
b. Estimate quantitative mission needs and requirements
c. Define alternative mission concepts
d. Define alternative mission architectures
e. Identify system drivers for each

f. Characterize mission concepts and architectures
g. Identify critical requirements
h. Evaluate mission utility
i. Define mission concept (baseline)
j. Define system requirements
k. Allocate requirements to system elements

There are several problems associated with SMAD methodology. Major problems include its hard (non-flexible) requirement set, rapid narrowing of design choices, many qualitative choices based on expertise and experience, and localized choices. The focus on the constraints, such as cost, is one of the major pitfalls of this methodology: it limits the design space and hides potential useful architectures.

The idea of GINA process was formed in the face of shortcomings of traditional initial design methods such as SMAD design methodology. The Multi Attribute Tradespace Exploration (MATE) is an extension of the Generalized Information Network Analysis (GINA) method created by Shaw (1999). The MATE process is used in the preliminary phase of a space system's design and is intended for use in early stages of product development. The place of the MATE process in a spacecraft timeline can be seen in Figure 5.18. A brief description of the MATE process adopted from SSPARC is presented in the following subsections.

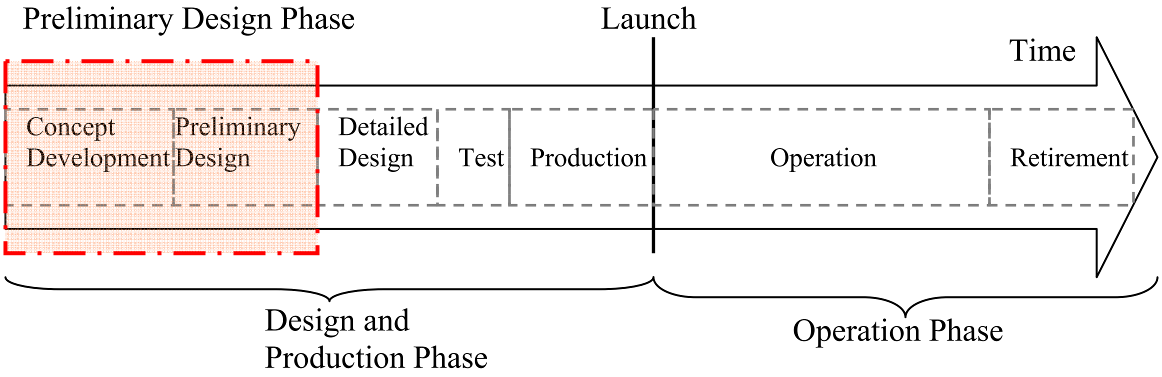


Figure 5.18. A preliminary design phase where MATE process is used.

MATE is a model-based and high-level assessment of many possible solutions to a specific problem. The major improvement of this method in comparison to the SMAD methodology is in avoiding premature concentration on a *point* solution. MATE gives the early decision makers a basis to explore a large number of solutions. It also creates a quantitative way to assess capabilities of a system.

Figure 5.19 shows the high-level schematics of MATE process. MATE process starts with definition and bounding of the mission concept. The next step is reduction of the qualitative user's needs to quantitative metrics. A limited number of attributes[20] are specified in this stage. The attributes must be quantifiable and capable of being predicted with reasonable fidelity. They are usually the results of effects of importance of the system to the user. After completing a set of attributes for a system, a formal Multi Attribute Utility (MAU) process is used to determine the utility of each attribute to the stakeholder. The individual utilities become integrated later into an overall utility. Utility is a dimensionless metric of goodness that is usually normalized to be between zero and one.[21]Sometimes utility can be given units such as cost per billable minute (for a broadband telecom system) or usefulness, to scientists, of scientific data and it can only be used as a relative metric.

---

[20] Attributes: "what the decision makers need to consider" and/or "what the user truly cares about. [SSPARC, 2005]

[21] Zero defines a dissatisfied user and one defines maximum user satisfaction.

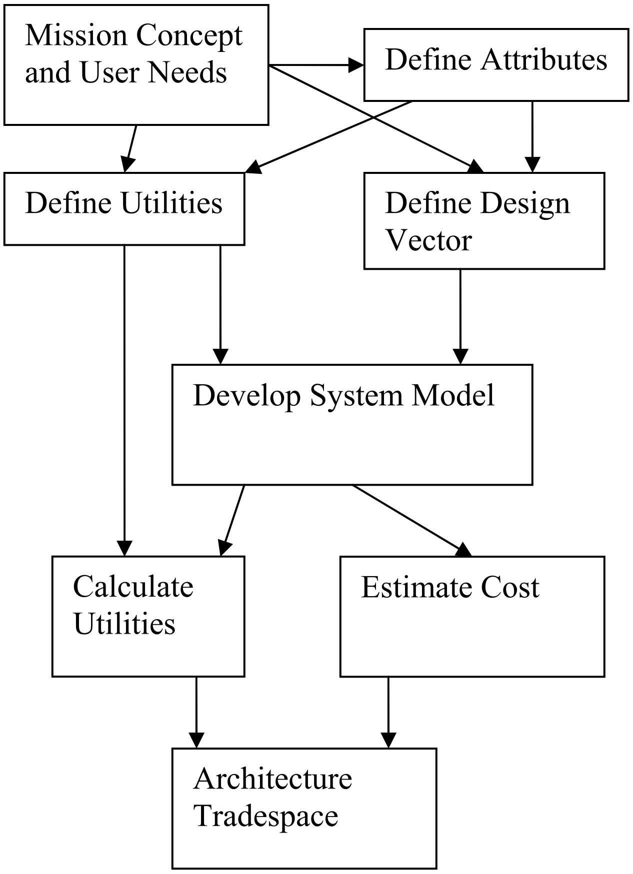


Figure 5.19. High-level description of MATE process (adapted from SSPARC 2005)

In the next step of the process, a design vector is being defined. A design vector contains a list of variables that define the system architecture. Usually the variables with largest effects on the system are kept in the design vector to avoid complexity of the modeling in the initial tradespace analysis. The next important step is to develop a system model. The model calculates the attributes of the system, given a set of values for the design vector. In this stage, some commercial tools such as Analytical Graphics' Satellite Tool Kit® (STK), and simple analysis techniques of SMAD are appropriate for use and integration with the model. The models may need to be customized for specific applications.

The next step is creating a tradespace of the utilities and costs. Multi attribute utility theory (MAU) and different cost models may be used in this stage. The result of the analysis is a database of tradespace. A tradespace contains thousands of potential architectures with resulting attributes, utilities, and costs. This database is the basis for the exploration of the tradespace. The most important part of the tradespace contains the most amount of utility for a given cost. This region is called the Pareto front. The designs that are not located on the Pareto front are dominated designs, meaning there are available better designs for the same cost or utility.

The process in Figure 5.19 is sequential. In case of change in circumstances or knowledge, the earlier decisions can be called into question. In case of change in user needs, utilities, attributes, or the design vector, the process can be repeated by modifying the analyses as necessary and rerunning them with changes in the procedure.

An example of MATE process on the Space Tug project can be seen in Figure 5.20. Some basic principles of MATE are being used in this chapter to create a flexibility tradespace. Therefore, familiarity with MATE process is a must. The benefits of using multi attribute tradespace explorations can be summarized as follows:

1. It offers a more robust quantitative method, than other available qualitative methods
2. It permits definition and quantification of attributes and utilities of a space system at a point of time in preliminary design phase
3. It contains a basic high-level modeling of the system to create the possible tradespace
4. Iterations are possible
5. It creates the possibility of exploring thousands of architectures and avoids fast narrow-downs to a specific point design

The above-mentioned benefits of MATE are the major drivers for our choice of it as our preliminary design phase methodology. We introduce several changes and variations to the original MATE process to capture the value of flexibility.

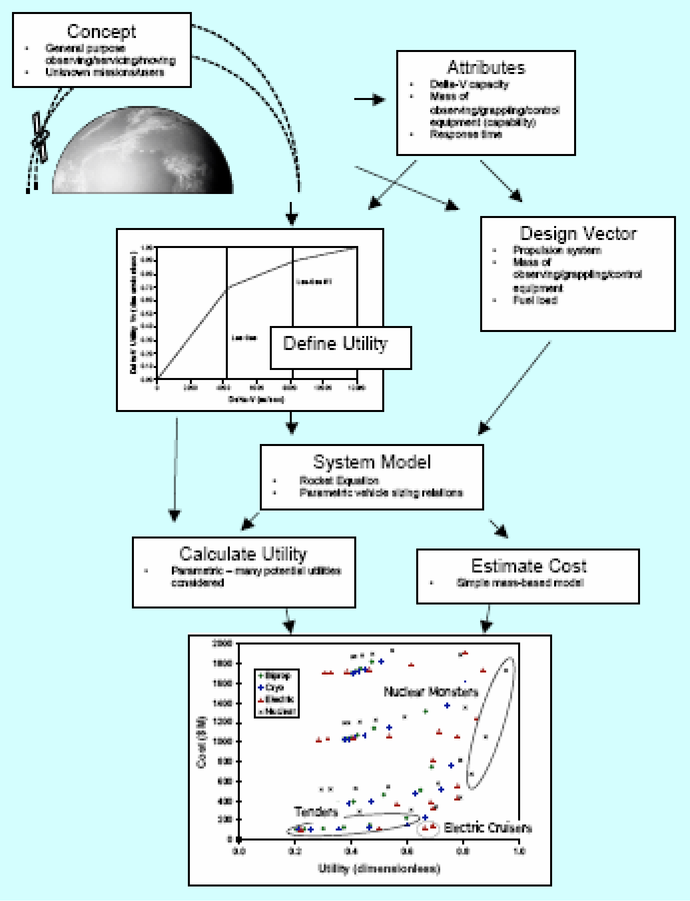


Figure 5.20. A sample of MATE process for the Space Tug project (from SSPARC Book, 2005)

5.2.2 Why the Current MATE Process Cannot Capture the Value of Flexibility

The MATE process is a very promising methodology in initial design phase tradespace explorations, but for the following reasons, the original MATE is not well suited to capturing flexibility in a system:

It does not recognize future uncertainties. Future uncertainties are not captured in the original process and MATE does not capture the expected value of the uncertain future benefits and costs of the system.

What you see is *not* what you get: The specifications of a chosen architecture show the nominal specification of that system. For example, the performance and cost of a specific architecture change over time; specifically, at the time of launch and operation of the space system, the performance and cost may vary from what is captured in the initial design phase.

The methodology has a *static* point of view. In fact, it acts as a snapshot of a system at a point of time, the status quo, separated from the past and future

The flexibility of the architectures in the face of future uncertainties can not be determined with the original MATE process. A tradespace created by MATE only shows the nominal cost and utility of architectures.

The utility theory used in the process does not capture any future extra benefits or utilities. Utility theory deals with the status quo utility of an attribute, and has a *static* view of the architecture. It cannot capture the value of *changing* architecture.

The above characteristics of the current MATE are obstacles to capturing the flexibility of architectures in the resulting tradespace. As a solution, a merger of the 6E flexibility framework and MATE is suggested and discussed in the following section of this chapter.

5.2.3 Merging the 6E Flexibility Framework with the MATE Process

Before constructing a merged framework, let us look at the six elements of flexibility and their current existence or absence in MATE process. The resulting tradespace of a merged framework should suffice to capture all six elements of flexibility.

First Element: System Boundary

The original MATE process takes into account the system boundary in the initial steps of the process. In the first step, which is the mission concept and user's need, the system to be studied is defined and the boundaries are drawn unmistakably. It should be clear that the tradespace is designed to perform trade-offs on a single satellite, a cluster, a constellation, or an enterprise.

Second Element: Time Window

A tradespace of flexibility should be able to contain the information related to changes and uncertainties, which happen in a *time window*. As discussed in Chapter 4, the choice of time window affects our view of a system. Short-, medium-, and long-term time windows show different values of flexibility in a system, because they contain different types and numbers of uncertainties. If the starting point of a time window is considered at the beginning of the mission operation, we can imagine the original MATE tradespace being transformed to the tradespace at t_1 which shows the cost, benefits, and values of the architectures at that late point in time. The tradespace at t_1 is carried forward in time, swimming in the time stream and going through hypothesized uncertain future events till we stop the time progress at time t_2. The tradespace has gone through events and changes which may have had an effect on costs and performance/benefits of each architecture. The tradespace at t_2 is a snapshot of different architectures and how they will have performed in the future. Based on the type of events, the chance that the architectures are still producing the same value and cost is small. The architectures have most probably moved and changed their positions in the tradespace of costs and utilities at t_2. The next important step is to *capture the changes in value delivery of the architectures in tradespace between times* t_1 *and* t_2 in order to capture the flexibility value of each architecture. The new tradespace shows the *expected cumulative costs and benefits* of the architectures.

Third Element: System Aspects

The flexibility aspect of a system is crucial for capturing the *right* value of flexibility for a tradespace. Starting with no direction or aspect of importance in mind can lead to measuring flexibility in aspects which have the least importance to us. Therefore, the most important aspect of concern about the future of a system should be identified. Our main concern may be dealing with partial failure, change or expansion of a mission, lifetime, or other matters regarding our specific space system. The importance of the issue is relationship and mapping between certain types of uncertainties and aspects. If we want to have the flexibility to expand the operating capacity of a space system in the future, we are most probably concerned with market uncertainty and volatility. If we most desire life extension of a space system, we must be concerned with market uncertainty, uncertainty in lifetime of critical parts of the spacecraft, and uncertainty regarding new and more efficient technologies.

The flexibility aspect is chosen by the stakeholder. The stakeholder may want more than one aspect of flexibility implemented in the system. In that case, several flexibility tradespaces can exist for space systems architectures, with each tradespace showing the flexibility of a specific architecture with regard to the chosen aspect.

Fourth Element: Uncertainty

The MATE process in its current form cannot capture future uncertainty. The original method creates a tradespace which shows the nominal cost and benefits or utilities of architectures, frozen in time. These costs and utilities are calculated in an NPV way, not considering any uncertainty in a system. In the new merged methodology, an evaluation methodology based on the type of uncertainty is associated with and used in each tradespace.

Fifth Element: Degree of Access/Implementability

After the relevant uncertainties of the system are identified, a set of solutions is suggested in order to deal with those uncertainties. Each solution may be a set of modifications at the design level, a set of actions or modifications after the system is fielded, or a combination of design modification and operation changes. As an example, a satellite can be modified in the design phase to be serviceable and then at some point during its operation, be serviced. The sets of solutions/ alternatives/ options should be designed based on the degree of access to the system and how the solutions could be implemented. For example, in an interplanetary space probe, designing an option for physically servicing the spacecraft may not be feasible, while a software upgrade is a more probably feasible solution.

Sixth Element: Response to Change of Value Delivery

The original MATE tradespace is modified to capture the cumulative benefits and costs of the architectures in the specified time window, and in the face of uncertainty. Depending on the type of uncertainty, several methods, such as decision analysis and options theory, can be used in order to capture the expected benefits and costs (cumulative probabilistic benefits and costs) of each architecture over the specified time window.

5.2.4 FlexiMATE: A Suggested Framework to Measure Flexibility of Architectures in a Tradespace

The FlexiMATE is a suggested framework to capture flexibility in the initial design phase. The methodology uses parts of the original MATE process and combines it with the 6E flexibility framework which was discussed in section 5.1 of this chapter. This methodology can identify the flexibility of tradespace architecture with respect to a certain aspect of importance. The methodology follows the 6E framework with some modifications, presented as follows:

- From mission concept and user's need step in MATE process, define the system boundary.
- Define the time window in which the resulting architectures are studied.
- Define the system aspect of interest from the point of view of flexibility.
- Define the measurable benefits produced by the space system.
- Identify the relevant sources of uncertainties with respect to the chosen aspect.
- Choose an evaluation method based on the specified types of uncertainties the space system faces.
- The architectures created by the MATE part of the process are treated as baseline cases.
- A possible set of alternatives based on the degree of access to the space system is suggested. Each alternative is associated with achieving a certain *goal*, e.g., life extension of two years. From this stage, each alternative can be pursued separately to create a tradespace for that specific option or alternative, or they can be placed in the same tradespace concurrently (if the number of architectures is multiplied by the number of designed alternatives, which in some cases can create a very large tradespace).
- If the selected alternative necessitates changes in the original design of the architectures, run the MATE system model for alternative architectures. Then calculate the costs and benefits associated with changes in the original design. If no changes are needed, proceed to the next step.

- Through the chosen evaluation methodology, calculate the *expected benefits* and the *expected costs* associated with baseline architectures and alternative architectures.
- Calculate the difference of expected benefits and expected costs for each alternative architecture relative to its related baseline architecture.
- (optional)- If non monetary benefits exists, Prospect theory can be used to capture the *value* of extra gained benefits to the stakeholder.
- Create a tradespace of Δcost versus Δbenefits or prospect values for each architecture. Each point in the tradespace shows an alternative's *extra value* gained versus its associated extra cost. Each point shows an architecture's alternative or option which can contribute to acquiring flexibility in a system.

Figure 5.21 shows the schematics of the FlexiMATE framework.

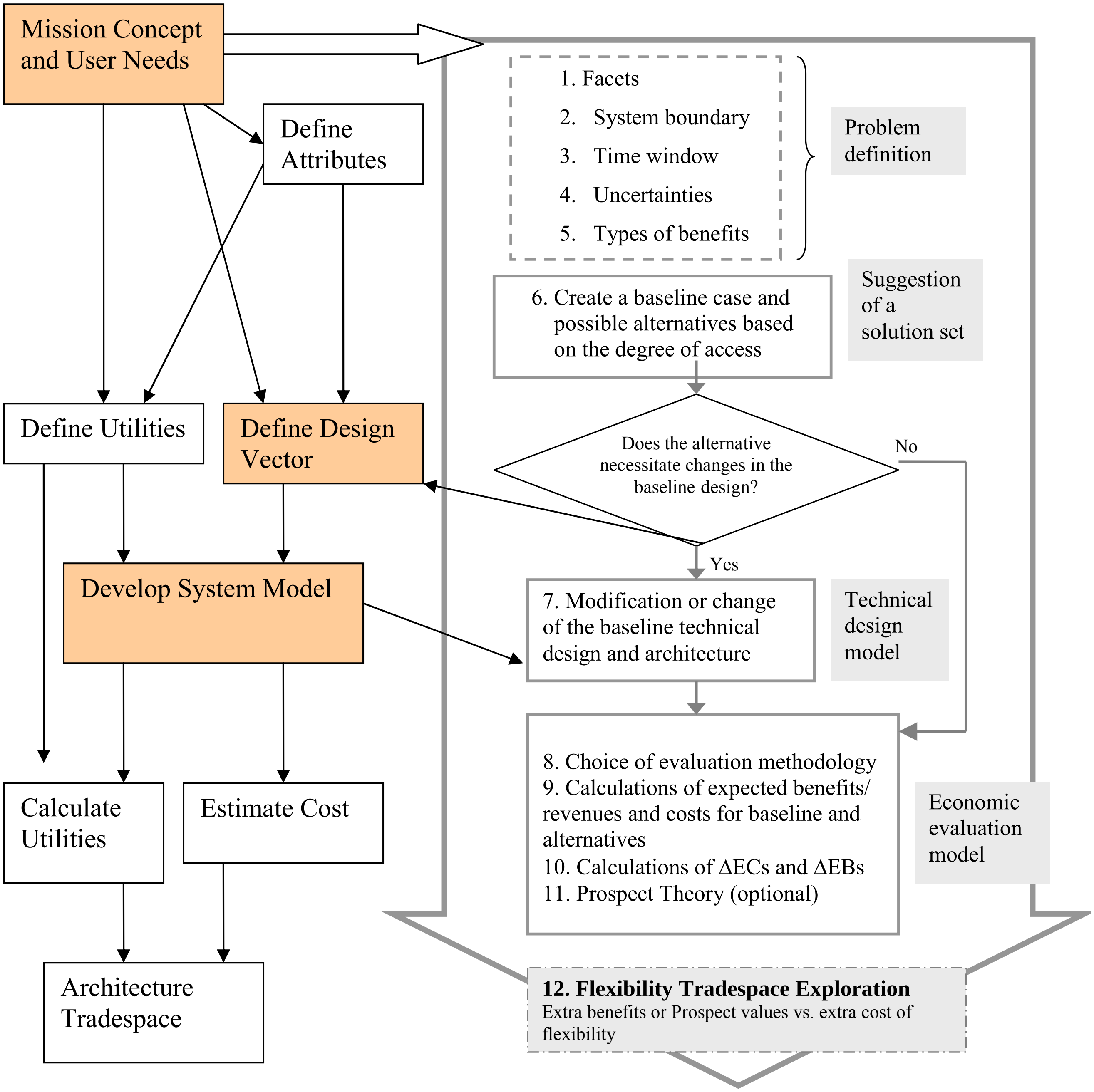


Figure 5.21. A schematic of the FlexiMATE framework.

5.3 Summary

In this chapter, we developed a flexibility measuring framework based on the six basic flexibility elements identified in Chapter 4. The twelve-step 6E Flexibility Framework was then described in detail and its relationship with the MATE process was discussed. The framework was presented both as a stand-alone framework and in combination with MATE (FlexiMATE). In the next chapters, we will be looking at how this framework can be applied to two actual space systems' design and operation.

References:

(Black and Scholes 1973)

Black, F. and M. Scholes, "The Pricing of Options and Corporate Liabilities" Journal of Political Economy 81, 1973, 637-654.

(de Neufville and Neely 2001)

Richard de Neufville and James Neely," Hybrid Real Options Valuation of Risky Product Development Projects," International Journal of Technology, Policy and Management, Vol.1, No.1, pp.29-46, Jan. 2001.

(de Neufville 2002)

Richard de Neufville et al., "Architecting/Designing Engineering Systems Using Real Options," ESD Symposium, Cambridge, MA May 2002.

(de Neufville 2004)

ESD.71 lecture notes by Prof. Richard de Neufville, Fall 2004, Massachusetts Institute of Technology.

(Howell 2001)

Sydney Howell, "Real options: evaluating corporate investment opportunities in a dynamic world," London, Financial Times Prentice Hall, 2001.

(Kahneman and Tversky 2000)

Daniel Kahneman, Amos Tversky, "Choices, values, and frames." Cambridge, Cambridge University Press, 2000.

(Keeney and Raifa 1993)

Keeney, Ralph L., and Raiffa, Howard, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs,* Cambridge University Press, Cambridge, UK, 1993.

(Merton 1973)

Merton, Robert C., "Theory of rational option pricing", Bell Journal of Economics and Management Science 4 (1), 1973, 141-183

(Neely 1998)

Neely, James, "Improving the Valuation of Research and Development: A Composite of Real Options, Decision Benefit Valuation Frameworks," PhD thesis, MIT, Department of Aeronautics and Astronautics, 1998.

(Saleh 2002)

Joseph H. Saleh. *Weaving time into system architecture: new perspectives on flexibility, spacecraft design lifetime, and on-orbit servicing*. PhD thesis, MIT, Department of Aeronautics and Astronautics, 2002.

(Schwartz 2001)

"Real options and investment under uncertainty: classical readings and recent contributions," edited by Eduardo S. Schwartz and Lenos Trigeorgis. Cambridge, MIT Press, c2001.

(Shaw 1999)

Graeme B. Shaw. *The generalized information network analysis methodology for distributed satellite systems*. PhD thesis, MIT, Department of Aeronautics and Astronautics, 1999.

(SMAD 1999)

Wertz, James R. and Larson, Wiley J., Space Mission Analysis and Design (SMAD), Microcosm Press and Kluwer Academic Publishing, 1999.

(Ross et al. 2004)

Adam M. Ross; Daniel E. Hastings ; Joyce M. Warmkessel; Nathan P. Diller, "Multi-Attribute Tradespace Exploration as Front End for Effective Space System Design," Journal of Spacecraft and Rockets 2004 , 0022-4650 vol.41 no.1 (20-28).

Chapter 6

6. Measuring Flexibility of a Commercial Space System: DirecTV Case Study

IN this chapter of this thesis, we apply and test our suggested 6E flexibility framework to a sample of commercial space systems to measure different aspects of flexibility in a commercial satellite. The chosen sample is DirecTV Group Inc., which owns one of the largest businesses in satellite TV broadcasting and is the first and fastest growing company in the U.S. providing direct-to-home television services. DirecTV Group is a digital multi-channel television service provider with more than 13.9 million customers and provides over 225 digital TV channels.[22] This company has a history of operating eight large satellites in the GEO orbit in the past, and has future plans for launching more satellites for incorporating new technologies, capturing new emerging markets, and replacement of currently existing old satellites on orbit. In this chapter, we will look at some aspects of flexibility, which are applicable to in-orbit satellite assets, and the planned future satellites of this company. The relevant uncertainties with regard to the satellite assets of DirecTV are identified and different approaches and alternatives for incorporating flexibility into its satellites are studied and compared to each other.

---

[22] DirecTV website http://www.directv.com

This chapter starts with a brief introduction to DirecTV, followed by a history and overview of the different divisions and markets of this company. Next, we present a brief review of technology and technical specifications of current and future DirecTV satellites and in-orbit assets. Financial market, stock information, and financial situation of the company follow next. Later in this chapter, the 6E flexibility framework is applied and values of flexibility are measured relative to the current state of the satellites in DirecTV Company.

6.1 DirecTV's History and Background: An Introduction

The first direct television broadcasting satellites were designed and launched in the 1980s. Germany launched TV-Sat 1, which used Ku-band transponders. Some examples of satellites with similar functions are Telediffusion de France's TDF-1, SES's Astra 1A, and Scandinavia's Tele-X. DirecTV, the first direct television service in the United States, was founded in 1991.DirecTV originated from Hughes Electronics Corporation, which started to lay the technical and administrative groundwork for planned direct-broadcast-satellite (DBS) services in the 1980s (Bass 2001). Hughes was granted permission to build a direct-broadcast-satellite by the Federal Communications Commission (FCC). The FCC authorized the use of three orbital slots with coverage over the United States for DBS services and determined a high Ku-band frequency (12.2 - 12.7 GHz) known as the broadcast-satellite-services (BSS) band for these satellites' use.

From December 1993 to June 1995, the first three satellites of DirecTV were launched and started operation in orbit shortly thereafter. These satellites provided digital quality, multi-channel TV programming over the U.S., which became a major competitor to cable companies. The spacing for satellites that are operating at the higher-powered BSS frequency is 9 degrees, in contrast to two degrees spacing for the traditional, lower-power Ku-band and C-band satellites. The major reason for wide spacing is to decrease interference from neighboring satellites and enable the use of small-diameter consumer antenna dishes (Bass 2001).

The major competition for DirecTV is cable television, which today has over 65 million subscribers. The advantage of cable television is in no up-front investment by the subscriber, and local distribution of channels. However, the major advantage of DirecTV is in providing a large number of channels versus the average number of 40 channels for cable TV.

The programming of DirecTV originates from the Castle Rock Broadcasting Center in Castle Rock, Colorado, and Los Angeles, California, which are digital broadcast facilities that convert standard analog programming into digital signals. These signals are uplinked to DirecTV satellites, located in geosynchronous orbit. The satellites retransmit the signals back to earth using different beams that cover the entire continental United States. The digital beams are directly received in the U.S. using receiving equipment and an 18-inch satellite dish.

The major technological advancement which enabled DirecTV satellites was digital compression. Before this technology advance, one analog broadcast-quality video signal was transmitted through one satellite transponder. Therefore, a typical C-band satellite was only able to transmit 24 video-programming services. Through digital compression advances, a digital video signal needed only 10 to 25 percent of a satellite transponder bandwidth. Therefore, a single transponder can now transmit six to 10 channels of programming. In addition, large high-power satellite designs provided a large power source for new powerful transponders.

DirecTV Group has improvement plans that include broadcast of local channels in high-definition format, advanced new programming and interactive services, and new digital video recorders with interactive capabilities. DirecTV has a "plan to continue to expand DirecTV's international programming lineup, grow our presence in rural markets, and by year-end introduce our Home Media Center that will provide an entertainment solution for the entire home."[23]

---

[23] Chase Carey, president and CEO of the DirecTV Group.

6.2 DirecTV Company and Its Services

The DirecTV Group Inc. was originally divided into three segments, which included DirecTV U.S., DirecTV Latin America (DLA), and Hughes Network Systems (HNS). It should be noted that DirecTV Group has gone through many changes in the company structure and ownership of the on-orbit assets since its formation. A brief description of each segment of the company is presented here.

DIRECTV U.S.

DirecTV U.S. is the largest provider of DBS television services based on the number of subscribers (13.9 million). DirecTV U.S. currently has a fleet of eight satellites, which distribute more than 850 digital video and audio channels, including about 125 basic entertainment channels, 31 premium movie channels, over 25 regional and specialty sports networks, an aggregate of over 600 local channels, over 35 Spanish and Chinese language special interest channels, up to 55 pay-per-view movie and event choices, and seven HDTV channels. DirecTV U.S. also distributes over 600 local channels (DIR 2005).

DirecTV Latin America (DLA)

DirecTV Latin America (DLA) is a provider of digital satellite television in Latin America, including South America, Central America, Mexico, and the Caribbean. DLA is primarily owned by The DIRECTV Group, as well as the local operating companies (LOCs) that sell the DirecTV service in Latin America. DLA currently has 1.6 million subscribers in 28 countries through the LOCs located in the various countries. Approximately 91% of the Latin American DirecTV subscribers are in Brazil, Mexico, Venezuela, Argentina, and Puerto Rico. The DirecTV Group also has an aggressive strategy in Latin America to buy its only satellite TV rival in the market and is planning for competition against local cable competitors.[24]

Hughes Network Systems

Hughes Network Systems (HNS) provides broadband satellite networks and services to consumers and enterprises. The HNS satellites, called Spaceway, are designed to provide

---

[24] PBI Media, LLC. SATELLITE NEWS, December 13, 2004

broadband Internet access service marketed under the name DIRECWAY. The first few Spaceway satellite contracts have been granted to Boeing Satellite Systems (BSS). The Boeing 702 geostationary satellites are designed to operate in the Ka-band spectrum. The first planned orbital slot for these satellites is 103 degrees West longitude. The Spaceway satellites include innovative onboard digital processors, packet switching, and spot beam technology which enables the satellite to provide services to small terminals, while onboard routers will enable mesh connectivity. Users of the system will be able to directly communicate with any other user of the system without requiring connection through a central hub (DIR 2005). HNS has already paid more than 94 percent of the $1.3 billion total cost of building and launching the three in-orbit satellites.

In October 2004 DirecTV Group decided to abandon its satellite internet plan.[25] The DirecTV Group announced an agreement for the sale of assets of HNS to SkyTerra Communications, Inc. The first two satellites of HNS, Spaceway 1 and 2, however, were not sold. These satellites have been changed and reconfigured to support the DirecTV satellite television and are scheduled for launch in 2005 together with DirecTV-8 satellites.

6.3 Description of DirecTV Satellites

DirecTV-1, 2, and 3

DirecTV-1, 2, and 3 are the first three satellites of DirecTV Company in orbit. The three satellites collectively provide more than 200 TV channels. DirecTV-1 was launched with an Ariane 4 in December 1993, DirecTV-2 with an Atlas-2A rocket in August 1994, and DirecTV-3 in June 1995, on an Ariane-42P H10-3 rocket. All three spacecraft are HS-601 body-stabilized models, which are designed and built by Hughes Space and Communications Company (HSC). Each spacecraft measures 23.3 feet (7.1 meters) across with the two transmit antennas deployed, and 86 feet (26 meters) long from the tip of one four-panel solar array wing to the other. Figure 6.1 shows an HS-601 model DirecTV satellite. The satellites are located at 101 degrees West longitude in GEO orbit.

---

[25] PBI Media, LLC. SATELLITE NEWS, December 13, 2004

Figure 6.1. An image of the DirecTV HS-601 satellite

The DirecTV-1 spacecraft has 16 transponders, which are powered by 120-watt traveling-wave tube amplifiers. DirecTV-2 and DirecTV-3 have reconfigured amplifiers to provide 8 channels with 240 watts. The amplifiers are suitable for analog or digital signals, and they are capable of transmitting high-definition television (HDTV) signals as well as CD-quality audio. The solar panels generate a combined 4300 watts of electrical power and a 32-cell nickel-hydrogen battery for power supply during eclipse.

The three DirecTV satellites operate in the BSS portion of the Ku-band spectrum (12.2-12.7 GHz) with circular polarization. They can deliver 48 to 53 dBW radiated power over the United States. Each spacecraft weighs around 3800 pounds (1727 kg) at the beginning of its life on orbit. Each spacecraft has an HS-601 model body which is composed of two main modules. The bus module is the primary structure that carries launch vehicle loads and contains the propulsion, attitude control, and electrical power subsystems. The payload module is a honeycomb structure that contains the payload electronics, telemetry, command, etc. Other parts, such as reflectors, antenna feeds, and solar arrays, can be attached directly to the primary module, and antenna configurations can be placed on three faces of the spacecraft bus.

On July 4, 1998, the main spacecraft control processor (SCP) aboard the DirecTV-1 satellite failed. Therefore, the control of the satellite was automatically switched to the spare SCP and the spacecraft continued its normal operation. A similar failure happened to DirecTV-3 satellite on May 4, 2002. DirecTV-3 was moved to a graveyard orbit in October 2002 but returned back to operation in 2003, when it was leased to Telesat. Telesat used the DirecTV-3 as backup for its troubled Nimiq-2 at 82 degrees West under the designation *Nimiq-2i*. The satellite has been moved in 2004 to back up *Nimiq-1* and is now operated under the name *Nimiq-3*.

DirecTV-1R

DirecTV-1R was launched in October 1999 in order to expand the channel capacity and on-orbit redundancy of the DirecTV satellite cluster. The satellite was basically intended to replace DirecTV-1, which still stayed in orbit as a backup satellite. DirecTV-1R is located close to the other three DirecTV satellites.

The DirecTV-1R spacecraft carries 16 Ku-band transponders, for additional Ku-band capacity that is used to deliver new programming services. The satellite delivers 7.7 kilowatts of power, which is nearly 30 percent more power than its predecessor models. The Hughes 601HP model uses gallium arsenide solar panels and other technological advances to provide a larger power capability.

DirecTV-4S

DirecTV-4S was launched in November 2001 and was the first spacecraft in the DirecTV fleet to use highly focused spot beam technology. The spot beam technology enables DirecTV to provide its local channel programs in metropolitan markets. DirectTV-4S also functions as a redundancy in orbit. The satellite is a Boeing BSS-601HP model, which carries spot beams payload for local channels, and a national beam payload.

DirecTV-4S operates on the Ku-band frequency. The spot beam payload has a total of 38 traveling wave-tube amplifiers (TWTAs) which are powered by a combination of 30-watt, 45-watt, 65-watt, and 88-watt TWTAs. The national beam payload has two active transponders with further capability for two active high-power and six active low-power transponders.

DirecTV-5 and 6

DirecTV-5 and 6 were launched in May 2002 and March 1997, respectively. The two spacecraft were originally purchased from PrimeStar Company in 1999 and they were renamed to DirecTV-5 and 6. The two satellites were designed by Space Systems Loral (LS-1300 model). The original names of the two satellites were Tempo1 and Tempo 2, which belonged to TeleCommunications satellite, Inc. (TCI), and its partner PrimeStar. The companies lost their GEO slot in an auction to MCI for a DBS FCC license for $682M.

The bus of each spacecraft is a three-axis body-stabilized LS-1300 platform designed by Space System Loral. Each satellite carries 32 high-powered Ku-band transponders at 115 watts, which can be switched to a 16 transponders at 220 watts configuration. The total transmitter power of each satellite is 3500 watts.

It should be mentioned that DirecTV-6 became damaged by a solar flare in April 1997, a month after its launch. The solar flare disabled three transponders and damaged the solar array, which caused three power outages in later stages of the satellite lifetime.

DirecTV-7S and 9S

DirecTV 7S was launched in May 2004 and DirecTV-9S is scheduled for launch in 2006. The two satellites are both Space Systems Loral LS-1300 models. The purpose of these two satellites is to serve the growing market with local channels and add new services. DirecTV-9S is to function mostly as a backup for DirecTV-4S and 7S.

The satellites are designed for a lifetime of 15 years with enough propellant to maintain station-keeping and orbital stability. Each satellite is capable of operating in two modes. In the first mode it can provide high-quality local and national digital video service, which is broadcast through 27 beams with 54 transponders, and in the second mode it uses 44 transponders broadcasting through 30 beams. The total power at the beginning of the life of each satellite is 13 kWs.

DirecTV-8

DirecTV-8 is planned for launch in 2005. The contract for the satellite has been granted to Space Systems Loral for an LS-1300 platform. The satellite weighs 3800 kg with an 8.5 kW power and a designed lifetime of 15 years. The satellite’s function is to support the current and next generation higher coding rate services that DirecTV provides. Figure 6.2 shows DirecTV-8’s design.

Figure 6.2. DirecTV-8 Satellite

DirecTV-8 has a Ka-band payload that uses the full 1,000 MHz of Ka-band communications bandwidth available to link DirecTV facilities. This new payload is a part of DirecTV's dramatic infrastructure development for the upcoming launch of local digital and high definition services in the Ka-band.

DirecTV-10, 11, and 12

Three of the satellites are planned to be launched in 2007, with one of them remaining as a ground spare satellite (DirecTV-12). The contract for these satellites was granted to Boeing in September 2004. All three satellites are designed based on Boeing 702 model satellites (BSS-702). These spacecraft will provide DirecTV with unprecedented national and local broadcast coverage in High Definition Television (HDTV) and will operate in the Ka-band. A suggested design of such a satellite can be seen in Figure 6.3.

Figure 6.3. DirecTV-10

Table 6.1. Major DirecTV satellites' information (source:)

Satellite	DirecTV-1, 2, 3	DirecTV-1R	DirecTV-4S	DirecTV-5, 6	DirecTV-7S, 9S	DirecTV-8
Contractor	Hughes	Hughes	Boeing	SSL[26]	SSL	SSL
Lifetime (years)	12	15	15	12	12	15
Mass (kg)	2860	3446	4260	3640	5483	3800
Configuration	HS-601	HS-601HP	BSS-601HP	LS-1300	LS-1300	LS-1300
Transponders	16 Ku-band	16 active Ku-band and 4 spare	48 Ku-band	32 Ku-band	54	36 Ku-band and Ka-band

Spaceway 1, 2, and 3

Spaceway satellites were originally designed to provide broadband internet access. The original service goal was to provide direct site-to-site connectivity at rates of 512 Kbps and 2 Mbps for remote locations and up to 16 Mbps at larger locations. The baseline satellite's design has Ka-band transponders, and contains on-board digital processing, packet switching, and spot-beam technology. Each satellite has a capacity of 10 Gbps in comparison with 1 – 1.5 Gbps supported on Ku-band satellites.

The Spaceway satellites operate on 12.3 kW of power and weigh 3842 kg. Figure 6.4 shows a Spaceway in stowed and deployed situation. DirecTV has modified the original design in order to use the Spaceway satellites for broadcasting of digital high definition TV. The Spaceway satellites are based on the Boeing 702 platform design, and considered to be one of the most complex commercial satellite systems manufactured. Each satellite has a flexible payload with a steerable downlink antenna that can be reconfigured when operating on orbit.

---

[26] Space Systems Loral

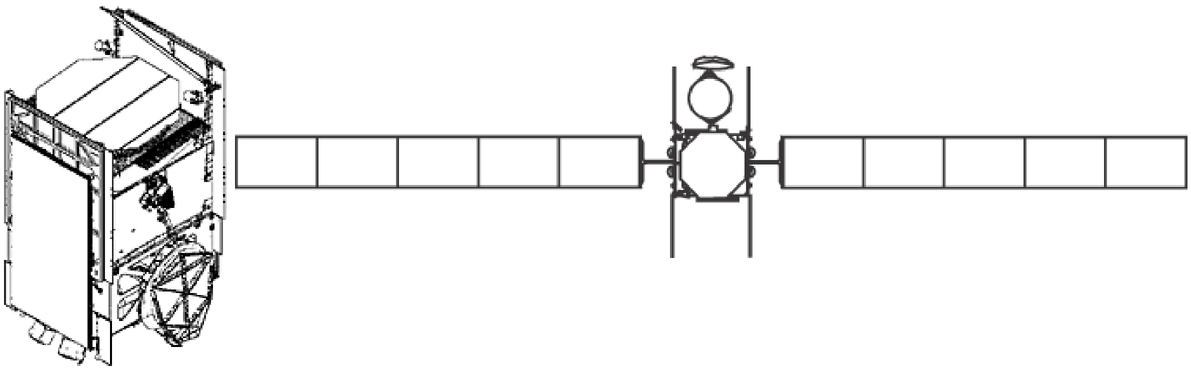


Figure 6.4. Spaceway satellite in stowed and deployed position. (source:)

The timeline of launch and operation of the current DirecTV satellites and future planned satellites can be seen in Figure 6.5. The currently presented situation of operations and plans of the company is considered as a baseline case and the alternative ways of achieving flexibility in such a system are studied later in this chapter.

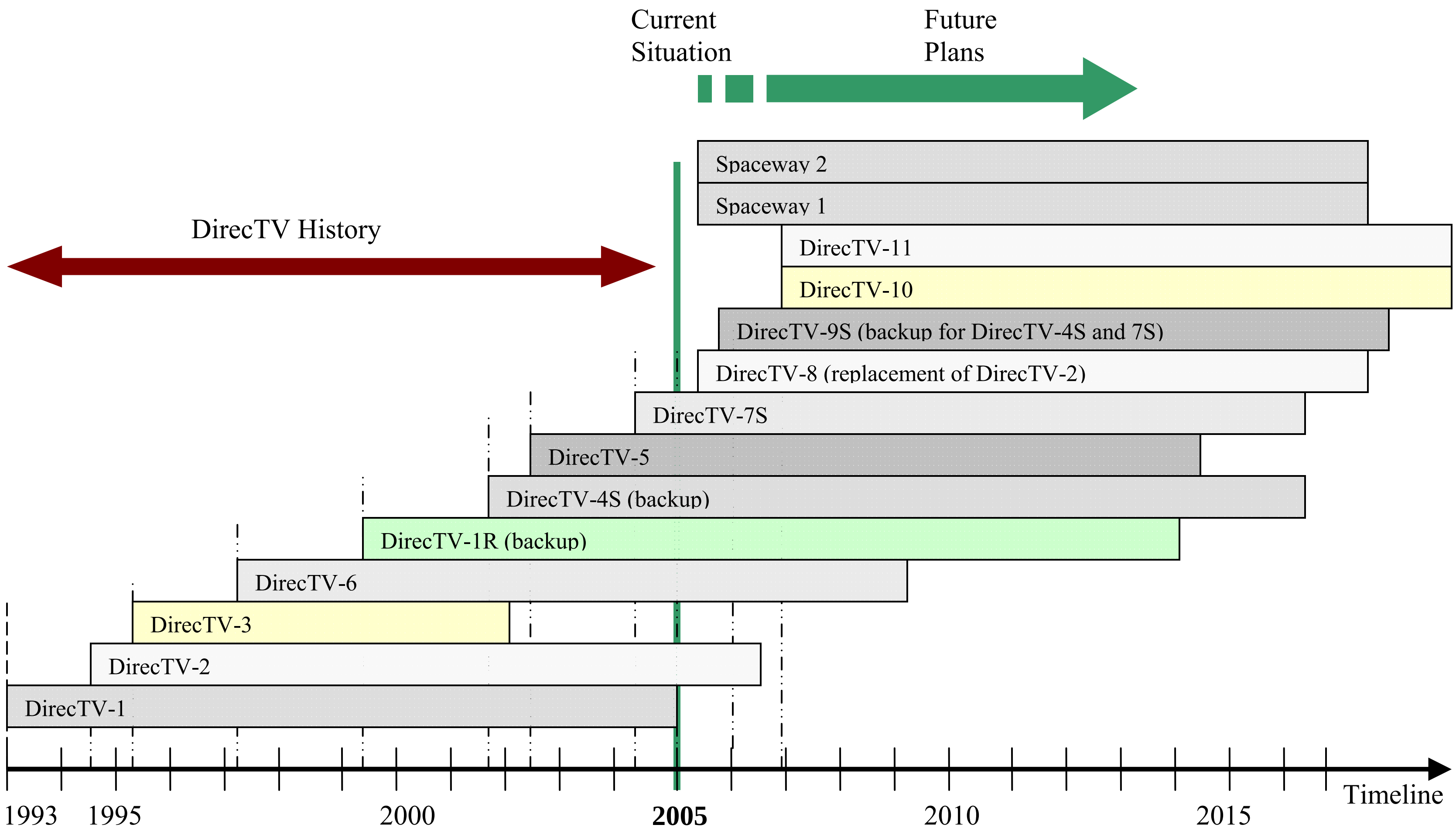


Figure 6.5. The timeline for DirecTV company satellites and their lifetime.

6.4 Satellite Platforms

SSL product platform:

The LS-1300 platform is used for a wide range of satellite designs. The satellite power ranges from 5 to 12 kW throughout the lifetime of the spacecraft. The on-board transmitter power is more than 5000 RF watts which enables the platform to accept more than 70 active transponders. The basic launch mass is approximately 5500 kg. The design of the platform can also be modified to accommodate larger and more power-consuming payloads. The modified models can accommodate power ranges from 12 to 18 kW during the lifetime of the satellite and can carry more than 90 active transponders. The launch mass of the modified model is approximately 6700 kg. The LS-1300 models can be fit into a 5-meter launch vehicle fairing (LOR 2005).

Boeing 601 platform:

The Boeing 601 platforms were first introduced in 1987 as a large spacecraft platform. Hughes Electronics Corporation owns the original design for a high-power, multiple-payload satellite for applications such as direct television broadcasting and mobile communication. All 601 platforms share the same design in order to create efficiency by production volume, tooling investment, and quantity buys.

The Boeing 601 body has two modules. The first module contains bus electronics, battery packs, and the propulsion subsystem. The second module has a honeycomb shelf design, which carries the communication equipment, electronics, and heat pipes. The modular design is very helpful in decreasing the manufacturing and testing time by parallel processing.

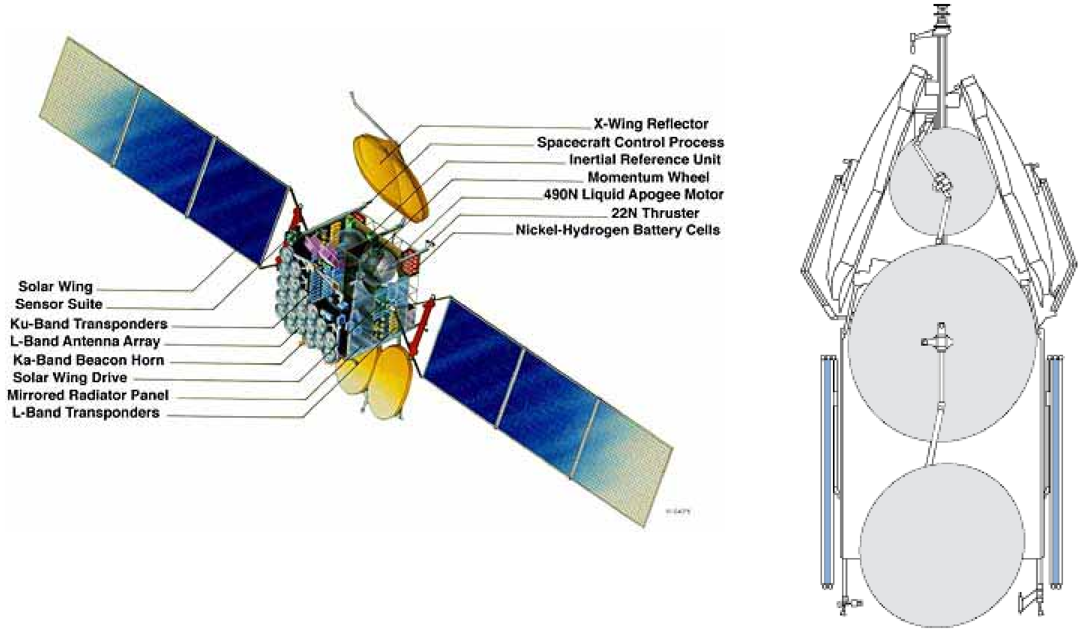


Figure 6.6. Boeing 601 platform, deployed and stowed (source: Boeing.com)

The basic 601 platform can carry up to 48 transponders and provide power up to 4,800 watts. The next generation of this model has been introduced since 1995 as Boeing 601HP models. The new design is able to carry up to 60 transponders and provide up to 10,000 watts of power. The 601HP model also utilizes gallium arsenide solar cells and optional xenon ion propulsion system (XIPS). The schematics of the Boeing 601 platform can be seen in Figure 6.6.

6.5 Communication Satellite Transponder Technology

A satellite communication payload consists of the satellite antennas and the transponder. A satellite transponder usually consists of a receiver, frequency converter, and transmitter package. Transponders are usually customized to the L-, C-, Ku-, X-, V- and Ka-bands and are used for different types of services which can be seen in Table 6.2. The transponder receives the signal, converts the frequency between the up-link and down-link, and boosts the signal through an amplifier before transmitting the down-link. Figure 6.7 shows two types of communication payload. Most of the currently existing payloads are considered to be *transparent* type, which only consist of RF amplification and frequency conversion. The suggestion for future communication payloads consists of *regenerative* or *processing* types, which include on-board processing (Evans 1999).

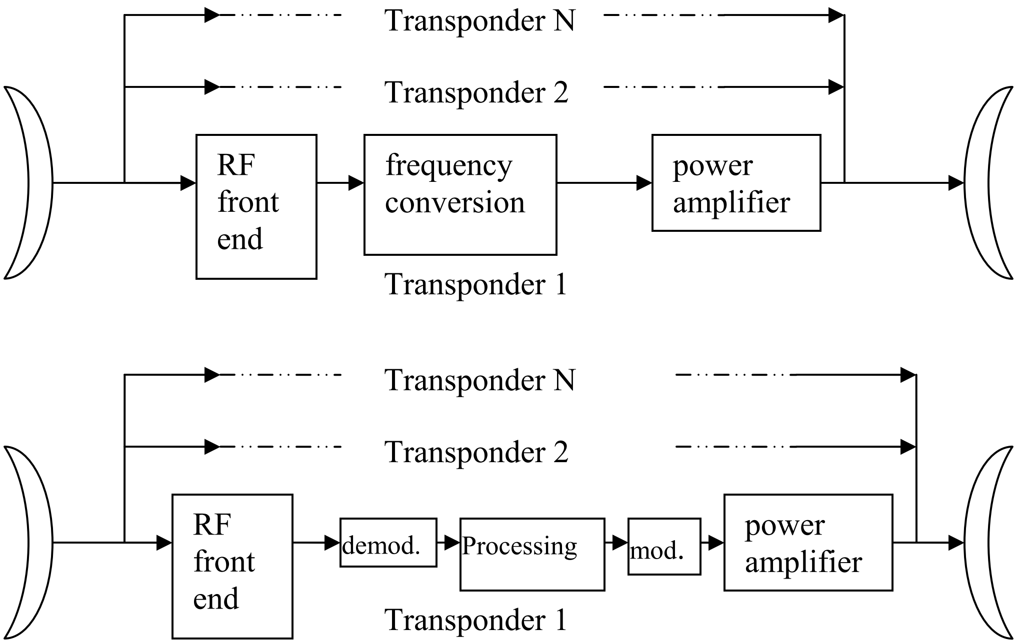
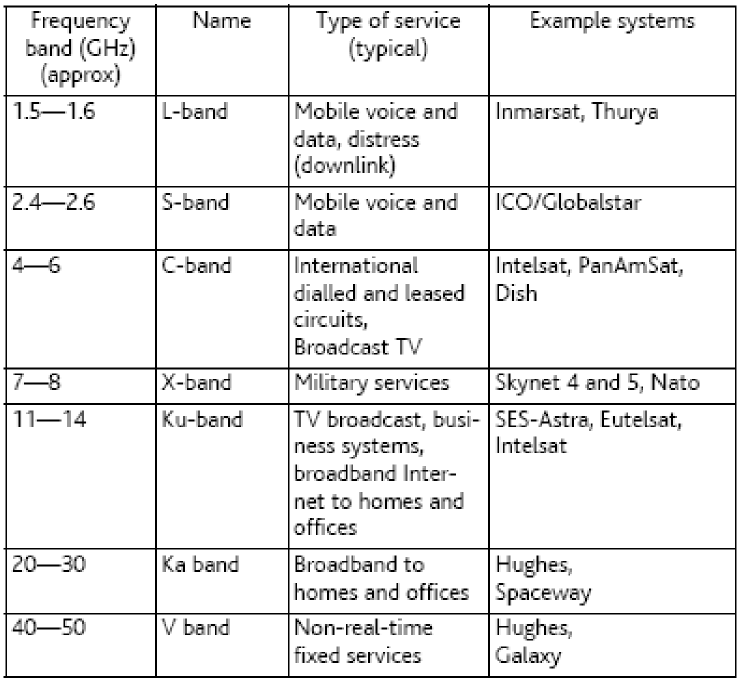


Figure 6.7. Communication payloads for conventional transparent satellite (top) and processing satellite (bottom) (from Evans 1999)

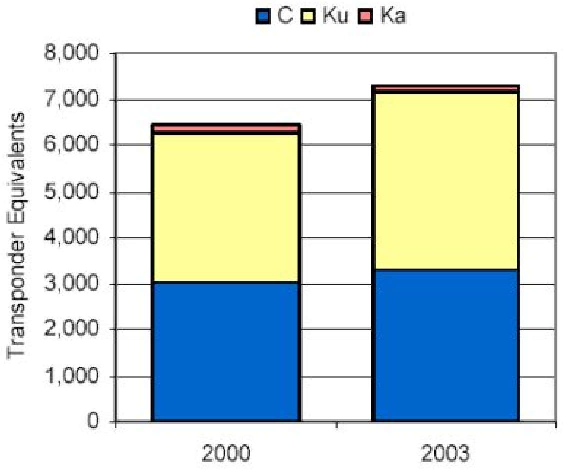
Table 6.2. Frequency band s and services (from Fitch 2003)



Frequency band (GHz) (approx)	Name	Type of service (typical)	Example systems
1.5—1.6	L-band	Mobile voice and data, distress (downlink)	Inmarsat, Thurya
2.4—2.6	S-band	Mobile voice and data	ICO/Globalstar
4—6	C-band	International dialled and leased circuits, Broadcast TV	Intelsat, PanAmSat, Dish
7—8	X-band	Military services	Skynet 4 and 5, Nato
11—14	Ku-band	TV broadcast, business systems, broadband Internet to homes and offices	SES-Astra, Eutelsat, Intelsat
20—30	Ka band	Broadband to homes and offices	Hughes, Spaceway
40—50	V band	Non-real-time fixed services	Hughes, Galaxy

There are three major types of communication satellite services, which include telephony, video, and data. Each of the three services has varying bandwidth requirements. Telephony has a submarket of international, domestic, and fixed telephone relays. Video consists of TV relay (cable and broadcast) and Direct to Home (DTH) TV submarket. The submarkets for data include private networks, ISP-to-Internet backbone, end-user internet (small office, home office, residential), in-flight entertainment, and mobile asset management (Futron 2003).

The amount of data transferred by a satellite is limited to the available spectrum. The current types of transponders most frequently used are C-, Ku-, and Ka-band transponders, which have a total number of 4500 active transponders on-orbit worldwide (Williams et al. 2003). Most of the Ku-band satellite transponders are commercially available in 27-MHz or 36-MHz bandwidths. Most of the transponders on board DirecTV satellites are Ku-band transponders. Ka-band transponders are more likely to be used for broadband applications because of their larger bandwidth (Iida 2003). The design of DirecTV's future satellites contains more Ka-band transponders. Ka-band is a suitable choice for multimedia satellites because of the large bandwidth, small antennas, and reduced interference.



	2000	2003
Ka	202	144
Ku	3,222	3,864
C	3,038	3,298
Total	6,462	7,306

Figure 6.8. Frequency trends by transponders (from Futron 2003)

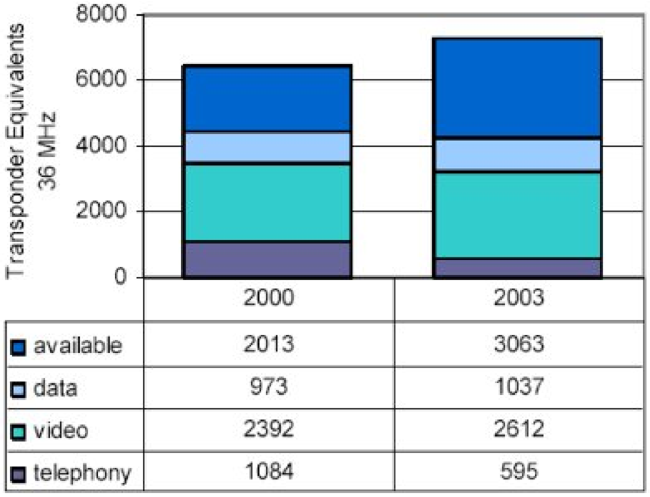


Figure 6.9. Capacity trend by application (from Futron 2003)

Compression is one of the major reasons for the evolution from analog to digital satellite transmission. Digital transmission has two reasons for superiority over analog transmission. First is the fact that digital signals are more resistant to the adverse effect of noise, and can tolerate an order of magnitude more noise than an analog transmission. The second benefit is the availability of digital compression techniques. After an analog signal is transformed to a digital one, digital computer techniques can be used to compress the required bandwidth needed to transmit the signal by one or two orders of magnitude. Therefore, the digital signals can be sent using much less bandwidth in comparison with analog transmission.

There are many different types of digital compression techniques. For example, one of these methods uses the fact that not many bytes in the second frame of a picture differ from the first frame. The second method uses the fact that many scenes have lots of repetition of identical pixels. Motion prediction is another way of reducing the amount of data. One other example of such compression techniques uses the fact that the human eye is not equally sensitive to all colors or to changes in the colors and intensity between adjacent colors. After a scene is converted from analog to digital, any of the above-mentioned techniques can be used to reduce the amount of data needed for broadcasting. The most common standard used in satellite broadcasting is MPEG-2.[27] This compression

---

[27] Motion Picture Expert Group standard version 2

technique allows real-time compression and broadcasting and allows as many as eight channels of television to be transmitted by a transponder. Currently, new compression algorithms such as MPEG-4 are evolving, which allow for higher quality and higher levels of compression. However, the compression and encoding are much more complicated and time-consuming in comparison with MPEG-2 (Iida 2003). The improvement in such compression algorithms can have a substantial effect on use of each transponder on a satellite. A communication satellite's capacity can also be increased by allocation of more usable bandwidth, and by frequency reuse, which includes optimal multicolor channel transmission schemes (Verma 2004).

Future Trends

According to the market research by Futron (2003), the future trend of the commercial satellite transponders shows an increase in the percentage and number of the Ka-band transponders. Figure 6.10 shows the future trend of the transponder type. Table 6.3 shows the prediction of the future transponder technology (Iida 2003).

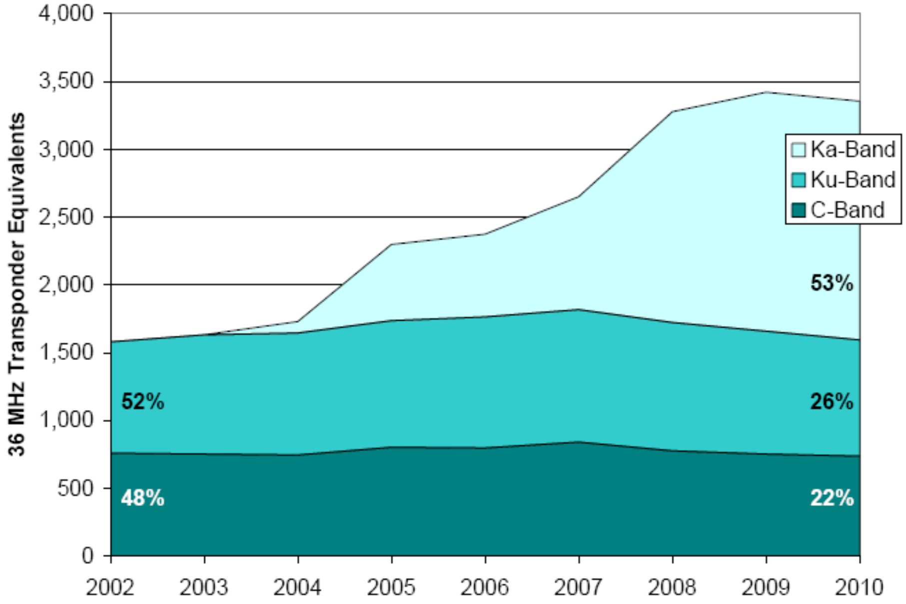


Figure 6.10. Future trend of transponders' capacity over the U.S. (from Futron 2003)

Table 6.3. Trends of key technologies for the future satellites (from Iida 2003)

Items	*Present*	*Future*
Type of transponder	Bent-pipe	Regenerative
Power amplifier	TWTA[28]	SSPA[29]
Type of antenna	Reflector	APAA[30]
Type of feed	Single-horn-feed	Digital-beam-forming feed/optical feed
On-board processor	N/A	High speed OBP[31]/ATM processor
Modulator/demodulator	N/A	Advanced intelligent software modem

6.6 DirecTV Financial

In this section, we briefly present the financial situation of the DirecTV Company and the related revenue, cost, and market volatility data, which will be used in calculating the value of flexibility. This section presents an overview of the financial performance of DirecTV Group.

DirecTV is a publicly traded company with common stock listed as "DTV" on the NYSE[32]. The company is 34% owned by Fox Entertainment Group, Inc. As the largest direct broadcast satellite provider, DirecTV's major competitors are Comcast, EchoStar Communications, and Time Warner Cable. As can be seen in Table 6.4, DirecTV has the second largest annual sales among its competitors, and the lowest number of employees.

Table 6.4. Sales of DirecTV and its major competitors in 2004 (from Hoover's AD & B database)

	DIRECTV	**Comcast**	**EchoStar Communications**	**Time Warner Cable**
Annual Sales ($ million)	11,360.0	20,307.0	7,151.2	7,699.0
Employees	11,800	74,000	20,000	30,000
Market Cap ($ million)	19,983.4	74,723.7	13,179.8	0.0

The number of subscribers of DirecTV is increasing annually at a considerable rate. Figure 6.11 shows a substantial increase in the number of subscribers from 1999 to 2004.

---

[28] Traveling wave tube amplifier

[29] Solid state power amplifier

[30] Active phased-array antenna

[31] On-board processor

[32] New York Stock Exchange

DirecTV has over 14 million subscribers as of April 2005, which on average generates $65 of revenue per subscriber.

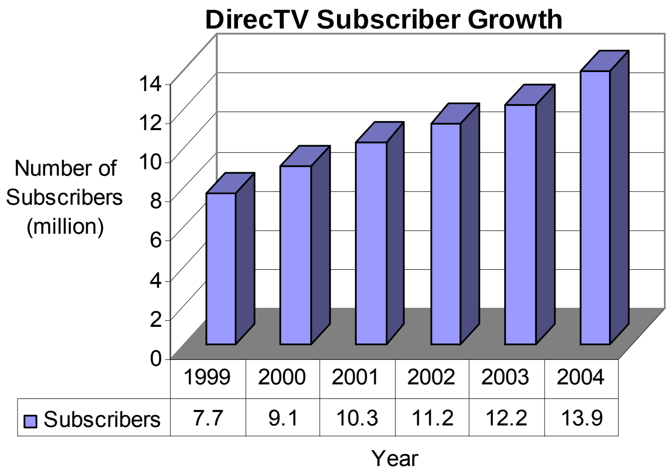


Figure 6.11. DirecTV subscriber growth from 1999 to 2004 (source data from DirecTV 2003&2004 annual reports)

The total revenue and net income data of DirecTV can be seen in Tables 6.5 and 6.6. This information will be used later in flexibility measurements. Figure 6.12 shows changes in the costs and revenues of this company over a period from 2000 to 2004.

Table 6.5. Total revenue, cost, and satellite assets of DirecTV Group., Inc., over a period of four years (data gathered from 16 DirecTV quarterly reports from 2000-2004)

Quarters of years 2000-2004	Total Revenue (Million dollars)	Total Cost (Million dollars)	Broadcast programming and other cost (Million dollars)	Satellite Assets (Million dollars)
Q1 2000	1703.1	1760.6	667.8	4230
Q2 2000	1837.0	1882.0	686	4230
Q3 2000	1688.5	1818.9	681	4230
Q4 2000	2059	2180.2	776	4230
Q1 2001	1893.0	2045.5	738.7	4372
Q2 2001	1985.1	2208.1	786	4540
Q3 2001	2103.3	2307	830	4617
Q4 2001	2280.6	2459	898	4806
Q1 2002	2024.8	2112	905	4922
Q2 2002	2192	2291	1080	4922
Q3 2002	2194	2178	965	4992
Q4 2002	2450	2432	1137	4992
Q1 2003	2227.3	2185	1061	4912
Q2 2003	2370	2230	1075	4892
Q3 2003	2570	2493	1186	4715
Q4 2003	2953	3065	1512	2408
Q1 2004	2510	2602	1263	2493
Q2 2004	2642	2671	1311	2597
Q3 2004	2861	4411	1218	1553
Q4 2004	3362	3799	1532	1560

Table 6.6. Annual revenue, net income and growth rates (from Hoover's AD & B database)

Year	Revenue ($ million)	Net Income ($ million)	
2004	11,360.0	-1,949.2	
2003	10,121.2	-361.8	
2002	8,934.9	-893.8	
2001	8,262.0	-621.6	
2000	7,287.6	813.0	
1999	5,560.3	-270.3	
1998	5,963.9	250.7	
1997	5,128.3	449.7	
1996	15,744.1	1,151.2	
1995	14,714.3	1,107.8	
Growth Rates	**12 Month**	**36 Month**	**60 Month**
Revenue Growth	12.2%	11.4%	14.1%

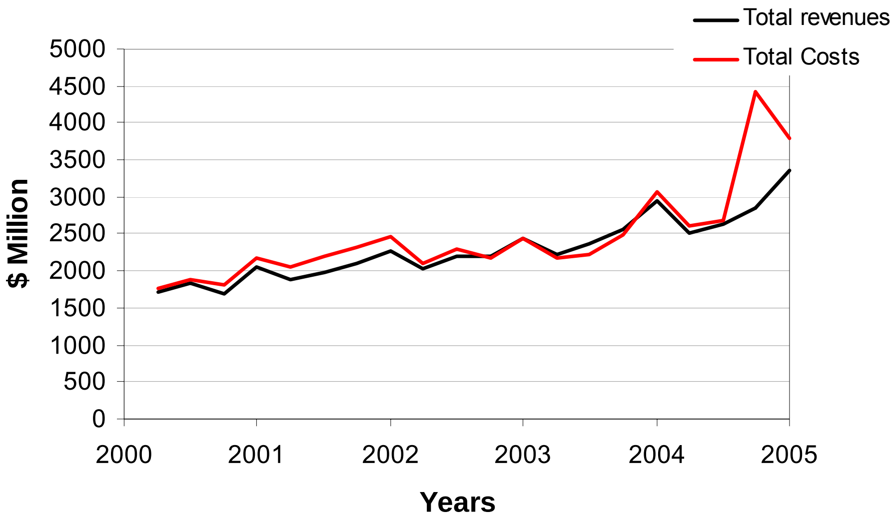


Figure 6.12. DirecTV revenue and net income from 2000 to 2004 (source: Hoover's AD&B database)

The stock information of the company is also of importance where the market uncertainty plays an important role. DirecTV stock volatility over periods of 3, 6, and 9 months has been 21.9%, 32.8%, and 19.48% respectively. Figure 6.13 shows the price and volume of DirecTV stocks over a five-year period. The stock market information on DirecTV stocks is also presented in Table 6.7.

Figure 6.13. Stock price change of DirecTV over a five-year period from 2000 to 2005 (from Hoover's AD & B database)

Table 6.7. DirecTV stock and market information as of March 2005 (from Hoover's AD&B database)

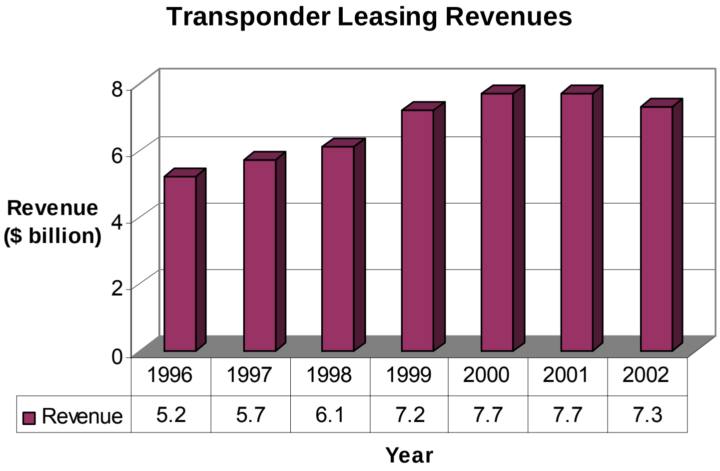
Last Close 31-Mar-2005	$14.42
52-Week High	$18.81
52-Week Low	$14.21
60-Month Beta	1.7
Basic EPS[33]	($1.19)
R&D Expense (million)	$49.00
Advertising Expense (million)	$170.10
% Owned by Institutions	81.00%
Market Cap (million)	$19,983.4
Shares Outstanding (million)	1,385.8
% Owned by Institutions	81%

---

[33] EPS (Earning per Share) is the portion of a company's profit allocated to each outstanding share of common stock. EPS indicates the profitability of a company, and it is calculated as follows:
EPS = (Net income – Dividends on preferred stock)/Average outstanding shares

6.7 Transponder leasing market

The satellite transponder leasing market is of considerable importance, because most of the communication companies lease some number of transponders on satellites in order to provide telephony, video, and data services. According to Williams et al. (2003), approximately 80% of on-orbit commercial satellites lease a number of their transponders. The business of leasing transponders has been profitable with high margins over the past thirty years. The business of leasing transponders has had a considerable growth due to a high demand for broadcast video and data services. Figure 6.14 shows the worldwide transponder leasing market from 1996-2002.



	1996	1997	1998	1999	2000	2001	2002
■ Revenue	5.2	5.7	6.1	7.2	7.7	7.7	7.3

Figure 6.14. Transponder leasing revenue, worldwide market (source: Williams et al. 2003)

Most of the transponder-leasing providers have been in the business for several years, as have Intelsat and PanAmSat. In 2003, a total number of 4058 transponders have been leased. The transponder leasing cost may vary based on transponder frequency, coverage areas, beam types, number of transponders, power levels, and the satellite lifetime. The transponder leasing cost averages $2.5 million per year per transponder in the U.S. Figure 6.15 shows the average transponder leasing cost worldwide. We assume that DirecTV is able to lease a number of its transponders if the projected market does not materialize. Therefore, leasing some number of transponders can be a source of extra revenue for DirecTV.

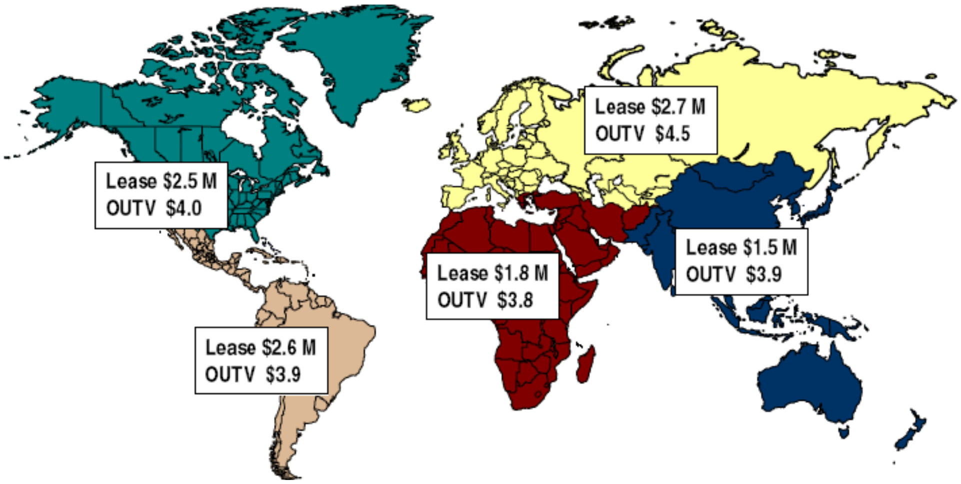


Figure 6.15. Transponder leasing market and annual lease prices (from Williams et al. 2003)

6.8 Flexibility Analysis

In this part of the chapter, we present two case studies. The first case study looks at the capacity expansion flexibility for a single DirecTV satellite over a period of eight years. The chosen satellite is DirecTV-8, which will be launched in 2005. In the second case study, we look at the DirecTV satellite fleet over a period of 15 years and address the flexibilities necessary to deal with market shifts and dramatic technological breakthroughs. Of course it should be noted that our case studies are limited in scope in that they do not address all the issues and dimensions that have to be taken into consideration in terms of a complex organization such as DirecTV. Decisions on flexibility often involve more complex business processes and involve organizational interactions that go beyond the basic evaluation of the costs and benefits of flexible alternatives for space systems assets and would require the boundary to be drawn around the enterprise of DirecTV rather than on a satellite or fleet level. Also important is that we are not exploring all possible alternatives, and we are liming ourselves to the most obvious alternatives. Therefore, these case studies are considered mainly illustrative of the types of flexibilities that can be addressed using the 6E flexibility framework, rather than serving as an exhaustive analysis of DirecTV’s operations. The consideration of enterprise-level flexibility will be part of the future work for this research.

6.8.1 Case Study 1: DirecTV-8 Service Capacity Expansion

In this section, we measure DirecTV-8 satellite capacity expansion and look at some alternatives to create flexibility in the satellite. Currently, DirecTV provides a total of 225 channels of movies, sports, local channels, pay per view, high definition TV, and digital video programming. The near-future goal is to expand to 1500 local and 150 national channels for an extended service. This goal is to be achieved through the launch of several satellites in 2005-2007, which will be the backbone for providing such an extended service. DirecTV-8 is one of these satellites and is scheduled for launch in 2005. In order to systematically define the problem and measure the flexibility, we apply our 6E flexibility framework step by step. A summary of our framework can be seen in Figure 6.16.

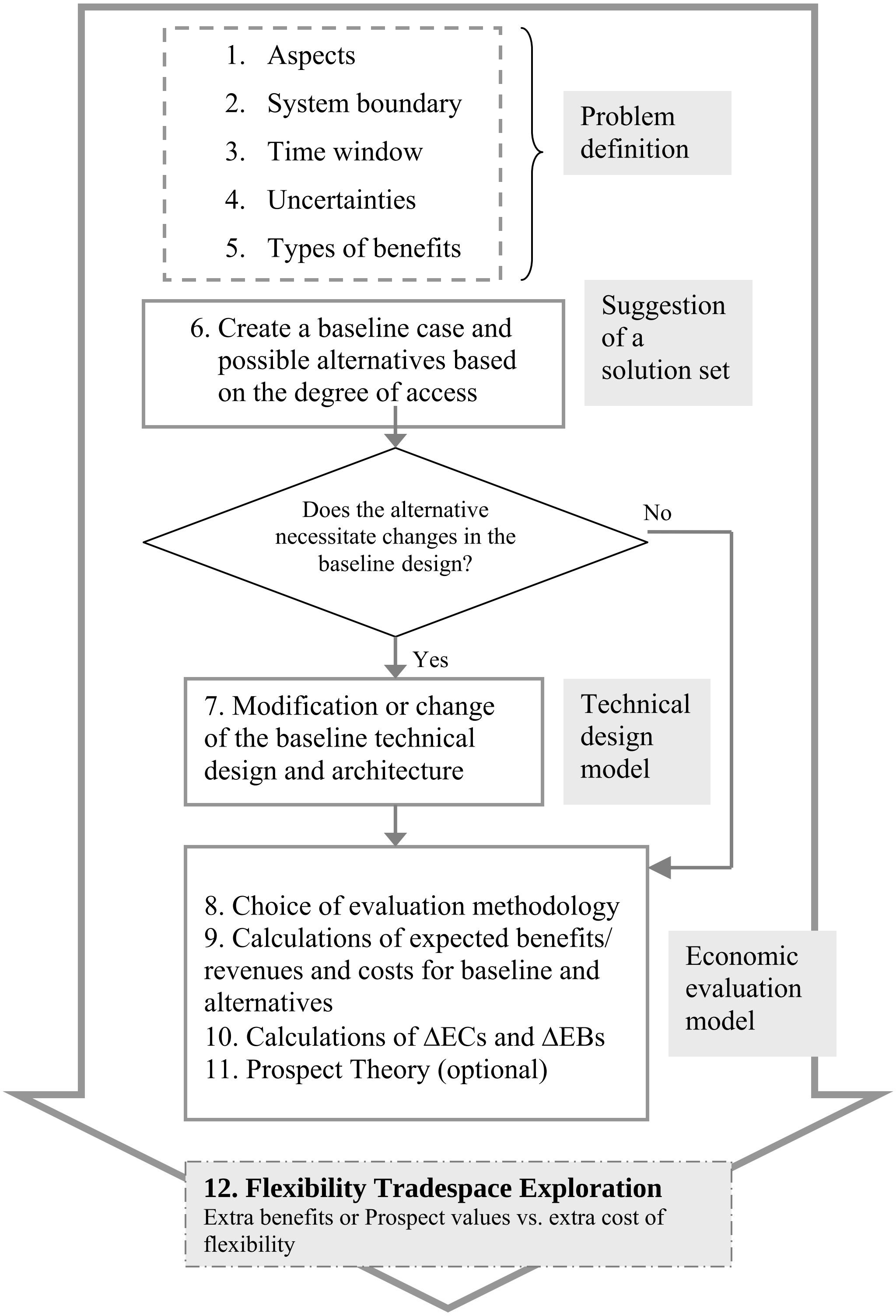


Figure 6.16. 6E flexibility framework

Problem Definition

In the first step of the 6E flexibility framework, we define the aspect of flexibility. In case study #1, we assume that the decision-maker is concerned with being able to expand the capacity for providing a larger volume of service, or *expansion flexibility*. Therefore, the goal of measuring flexibility for the baseline and alternatives would be to determine an alternative that can cope with changes in demand and technological progress in a timely and cost-effective manner.

In the second step, we define the boundary of the system of interest. For case study #1, we choose DirecTV-8 satellite as a member of DirecTV's satellite fleet. Therefore, the system boundary contains a single satellite of a fleet. DirecTV-8 is a Space System Loral (LS-1300 model) design, with a baseline mass, power, and lifetime of 3800kg, 8.5kwatt, and 15 years, respectively. The baseline satellite design accommodates 32 Ku-band and 4 Ka-band transponders.

In the third step, we choose a time window to study the flexibility of DirecTV-8. The chosen time window is from 2006-2013, an eight-year period. Therefore, all the revenue and cost changes to DirecTV-8 are of importance for measuring its flexibility. Figure 6.17 shows the problem definition for case study #1.

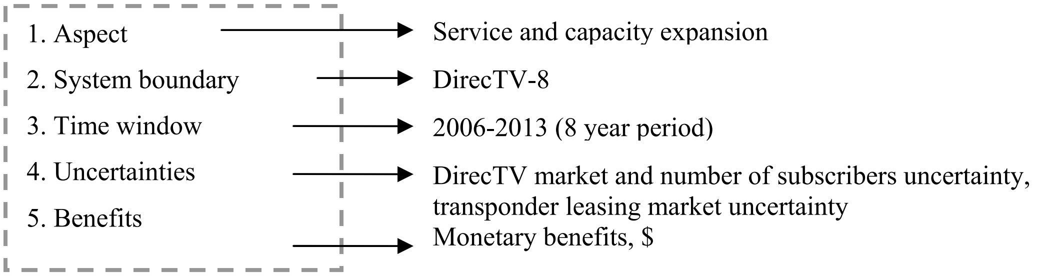


Figure 6.17. Problem definition for DirecTV case study #1

In the last step of problem definition, we define the relevant uncertainties for the chosen aspect, expansion flexibility. The major sources of uncertainty that affect DirecTV's revenue are extracted from DirecTV's annual report (2004). These major uncertainties include product demand and market acceptance, economic conditions, existence of new and desirable programming content and interactive features, competition, and technological risks. Our current model addresses the market and technological uncertainties associated with transponder technology. The other sources of uncertainty are identified to be the success and timeliness of satellite launches, in-orbit performance of satellites (including technical anomalies), loss of uninsured satellites, and uncertainties regarding the ability to access capital to maintain financial flexibility. The latter uncertainties, however, are not designed into our current model and can be explored in future work.

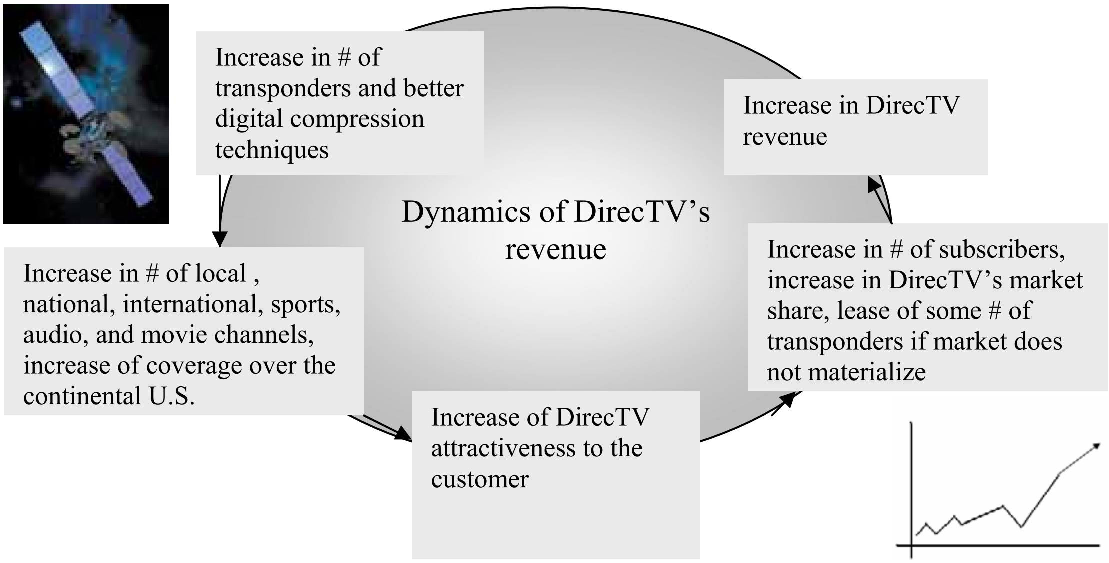
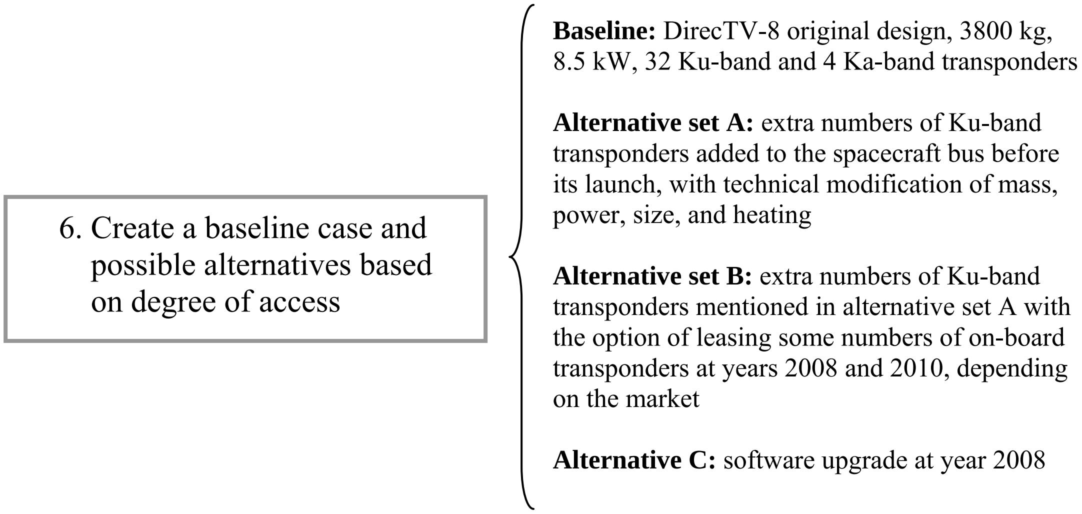


Figure 6.18. DirecTV-8 revenue as a function of number of Ku-band transponders for case study #1

The revenue created by DirecTV-8 is affected strongly by the number and the technology of the on-board transponders. Figure 6.18 shows the dynamics of DirecTV-8 satellite revenue. The increase in the on-board transponders and the use of better digital compression techniques enable the satellite to broadcast a larger number of local and national channels and provide better coverage over the continental U.S. A considerably better service (in comparison with cable companies, which provide less than ¼ the number of channels as DirecTV), creates an incentive for subscribers of cable companies to switch to DirecTV's service. The superior attractiveness translates to a faster annual growth of the number of subscribers, which eventually leads to higher revenue for the company. If the predicted market does not materialize, the extra transponders can be leased (An overview of the transponder leasing market was presented in section 6.7 of this chapter). In 2003, the market for transponder leasing had the capacity to absorb 4058 transponders with a projected growth of more than 5000 transponders in 2010. Therefore, we assume the market is receptive to leasing up to 20 transponders on board DirecTV-8. In addition, we assume that each leased transponder creates a \$2.5 M/year increase in revenue for DirecTV-8 (Futron 2003).

Creating a Baseline and Alternatives

In the next step of the framework, we define a set of alternatives that may create more flexibility with respect to capacity expansion. We consider the baseline case to be the current DirecTV-8 design with specifications that can be seen in Figure 6.19. The first set of suggested alternatives is to increase or decrease the number of on-board transponders from the baseline case. Alternative set A includes DirecTV-8 with 24, 28, 36, 40, 44, 48, and 52 transponders with all design modification to the power, thermal, and spacecraft bus. The second set of alternatives is to have the option of leasing a number of the alternative set A in the years 2008 and 2010. We will look at leasing 5, 10, 15, and 20 transponders based on the state of the market, if the satellite is generating a revenue less than $\Re_{\min}$. The last alternative looks at a software upgrade in 2008, with a probability distribution of more efficient digital compression techniques. Better digital compression algorithms make it possible to send more channels per transponder and therefore have the same effect on revenue as increasing the number of on-board transponders, but are associated with less cost and do not need a design modification.



6. Create a baseline case and possible alternatives based on degree of access

Baseline: DirecTV-8 original design, 3800 kg, 8.5 kW, 32 Ku-band and 4 Ka-band transponders

Alternative set A: extra numbers of Ku-band transponders added to the spacecraft bus before its launch, with technical modification of mass, power, size, and heating

Alternative set B: extra numbers of Ku-band transponders mentioned in alternative set A with the option of leasing some numbers of on-board transponders at years 2008 and 2010, depending on the market

Alternative C: software upgrade at year 2008

Figure 6.19. A set of alternatives and DirecTV-8 original design as a baseline case

Technical Model

The technical model task is to modify the baseline case design of the satellite to accommodate necessary changes for each alternative. The schematic of the technical model for case study #1 can be seen in Figure 6.20. For example, in case study #1, the alternative set *A* requires a change in the number of on-board transponders. The change in number of transponders increases or decreases the baseline case design of the spacecraft, and changes the power requirement and the spacecraft mass. DirecTV-8 has an LS-1300 bus which can accommodate up to 90 transponders on board the spacecraft. Each additional transponder translates back to power and mass increases.

Table 6.8. Typical Ku-band communication subsystem (from SMAD 1999)

Component	Quantity	Mass (kg) each	Mass(kg) total	Power (W)	Remarks
• Transponder	2	4.45	8.90		Generic Ku-band transponder
• Receiver				4.3	• 4-W RF output
• Transmitter				20.0	• Solid-state power amp
• Filters/switch diplexers	1	1.2	1.2	0.0	1 set
• Antennas					
• Earth cover	1	0.5	0.5	0.0	Earth coverage horn
• Parabola	1	2.0	2.0	0.0	Cross-link antenna
• Waveguide	1	0.7	0.7	0.0	
Total			13.3	24.3	

The power and mass specification of a Ku-band transponder can be seen in Table 6.8. The new power requirement necessitates the redesign of solar panels and secondary batteries. The electrical power subsystem (EPS) consists of silicon solar photovoltaic panels and nickel-hydrogen batteries. DirecTV-8's lifetime is 15 years and the destination orbit is a geosynchronous orbit. The daylight-required power is calculated as follows:

$$P_{sa} = \frac{\left(\frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d} \right)}{T_d} \qquad (6.1)$$

where T_e is the eclipse duration, T_d is daylight duration, P_e is the required power during eclipse, P_d is the required power during day time, and a peak power tracking regulation scheme with $X_e = 0.6$ and $X_d = 0.8$.

In the next step, we calculate

$$P_{BOL} = P_0 I_d \cos(\theta) \tag{6.2}$$

where P_{BOL} is the power at the beginning of life, $\cos(\theta)$ is the cosine loss, θ is the sun incidence angle, and I_d is the inherent degradation. The type of solar cell is silicon, with $P_0 = 202$ W/m^2.

Next, the required power at the end of life and the mass of the solar panel are calculated as follows:

$$P_{EOL} = P_{BOL}\left(1 - \deg radation/year\right)^{satellite\_life} \tag{6.3}$$

$$M_a = 0.04 P_{EOL}$$

Assuming that DirecTV-8 uses nickel-hydrogen (common pressure vessel design) batteries with specific energy density of 40-56 W-hr/kg, we can calculate the mass and cost of batteries for the new power requirement. We also consider the necessary modifications to the power regulation and control system.

Technical design model:
- A selection of Ku-band and Ka-band transponders
- New power requirement
- New thermal radiator design
- New solar panel and battery design
- Extra spacecraft bus modification
- Total mass calculation

Figure 6.20. Technical design model for the alternatives that need changes in the original DirecTV-8 design

After performing all required modifications in spacecraft design, the new mass and power of the modified spacecraft are calculated and used to determine the extra cost of modification and change in the cost model (economic evaluation model).

Economic Evaluation Model

In the economic evaluation model, we choose a suitable evaluation methodology based on the types of uncertainty of most importance. We identify two major uncertainties to be the market and technological progress uncertainty. The market uncertainty is modeled by binomial lattice analysis, which will be described shortly. The technological progress uncertainty, or the uncertainty of development of more efficient digital compression techniques, is modeled by a decision tree. The cost model is built based on the frequently used CER[34] (SMAD 1999) and also the detailed design modification costs and the operation costs. Brief descriptions of the above-mentioned models can be seen in Figure 6.21.

Economic evaluation model:

- Evaluation methodology: decision analysis and real options with binomial lattice analysis
- Revenue in \$, $\Re$ (service package, # of subscribers per package, premium charged per package, leased transponders, DirecTV market uncertainty for each package, transponder lease market uncertainty)
- Cost: C (original spacecraft, $\Delta C_{transponder}$, ΔC_{EPS}, $\Delta C_{thermal}$, $\Delta C_{IA\&T}$, ΔC_{launch}, $\Delta C_{operation}$, $\Delta C_{software}$)

Figure 6.21. Economic evaluation model for calculating the revenue and cost associated with each alternative

Market Model

We break down DirecTV’s market into four submarkets based on the different major groups of subscribers. The number of subscribers, revenue per subscriber, market drift, and market volatility in each group create the baseline revenue of the DirecTV company. We divide the current number of subscribers in year 2005 into four group based on the defined service packages in Table 6.9. The first group, which is called “Basic”, has the largest number of subscribers and provides basic satellite TV services. The second group, called “Premium 1” has 1.5 million subscribers and has a number of extra movie

---

[34] Cost Estimating Relationship

channels. The third group called “Premium 2” and has 2.5 million subscribers for a package of all extra movie and sports channels. The last group consists of a portion of the U.S. customers who are subscribers to the international channels. Table 6.9 shows the detailed breakdown of the above-mentioned markets.

Table 6.9. DirecTV service packages and the average revenue of each package per month in 2005

Service package	Revenue /customer /month	Market drift α	Market volatility σ	# of subscribers in 2005 (million)	Includes (in 2005)
Basic	\$45	8-12%	20%	9.5	125 channels of local and national TV, including 36 audio radio channels
Premium 1	\$68	12%	18%	1.5	Basic channels plus 7 HBO, and 12 Starz channel
Premium 2	\$93	16%	35%	2.5	Premium 1 channels, plus 10 Showtime, 3 Cinemax, and 25 sports channels
International	\$70	14%	30%	0.5	Basic package plus the following possibilities: Vietnamese: \$15/month South Asian: \$15- 29/month Italian: \$10/month Chinese: \$20-27/month Spanish: \$29-88/month

As can be observed in Table 6.9, the number of subscribers per package varies and each package has been modeled to have its own market and probability distribution. Each of the packages in Table 6.9 has a different number of subscribers and each market has different drift α and volatility σ. A binomial lattice model has been used to model the uncertainty in the number of subscribers for the four submarkets. Figure 6.22 shows the probability distribution functions for each of the four markets at the end of 2013, with the average number of subscribers per group specified on each distribution.

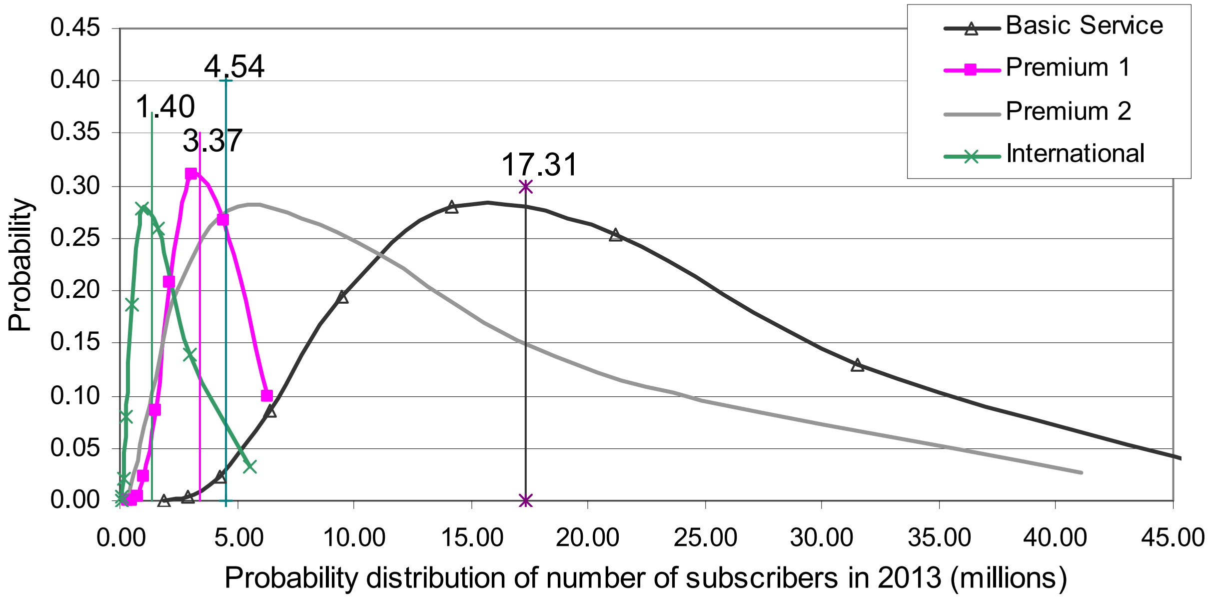


Figure 6.22. DirecTV four different packages (sub markets) and probability distribution for each market at the end of 2013

The binomial lattice model was introduced in 1979 by Cox, Ross and Rubinstein in a paper entitled, “Option pricing: a simplified approach.” Binomial lattice is considered as one of the most powerful tools to model market uncertainty and evaluate a variety of options (Chriss 1997). The binomial model is a discrete time model, as opposed to the geometric Brownian model, which is a continuous time model. We begin constructing a binomial tree by determining beginning and ending time. In our case study, the beginning time is 2005 and the ending time is 2013. The chosen time step, or δt , is considered to be one year.

We use a log-transformed binomial lattice methodology proposed by Trigeorgis (1996). If we are considering only one uncertain parameter *X*, an intermediate variable *Y* is defined in order to create a linear drift (log-transformation). Here, *Y* is the number of subscribers in each of the four submarkets, and we have:

$$\frac{dX}{X} = \alpha dt + \sigma dB$$

$$dY = \left(\alpha - \frac{\sigma^2}{2}\right)dt + \sigma dB \qquad (6.4)$$

where α is the expected drift, σ is the volatility, and δt is the time step of the simulation. The mean drift and volatility can be written as

$$E(\delta Y) = \left(\alpha - \frac{\sigma^2}{2}\right)\delta t = p\Delta Y + (1-p)(-\Delta Y) \qquad (6.5)$$

$$Var(\delta Y) = \sigma^2 \delta t = \left(p\Delta Y^2 - (1-p)(-\Delta Y)^2\right) - E(\delta Y)^2 \qquad (6.6)$$

The associated probability p and ΔY are calculated as follows:

$$\Delta Y = \sqrt{\sigma^2 \delta t + \left(\alpha - \frac{\sigma^2}{2}\right)^2 \delta t^2} \qquad (6.7)$$

$$p = \frac{1}{2}\left(1 + \frac{\left(\alpha - \frac{\sigma^2}{2}\right)\delta t}{\Delta Y}\right) \qquad (6.8)$$

The schematics of such a tree can be seen in Figure 6.23. We create four different lattices with different drift and market volatility for each sub market. An example of such a lattice for the Basic package market can be seen in Figure 6.24.

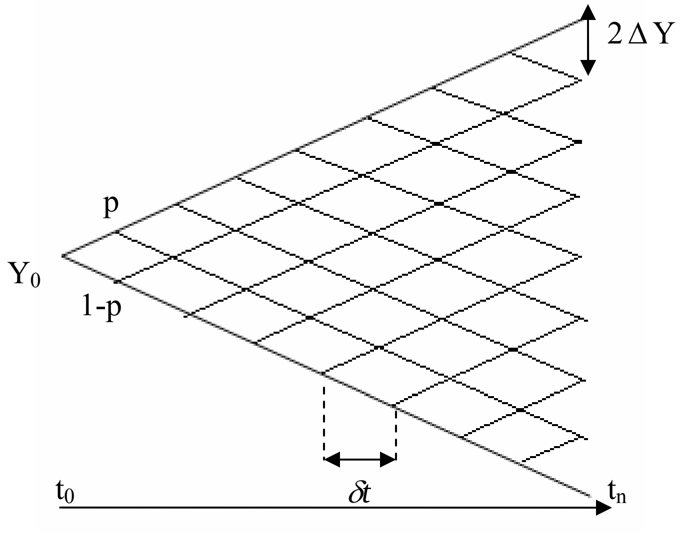


Figure 6.23. A schematic of a binomial lattice

OUTCOME LATTICE (number of subscribers)

2005	2006	2007	2008	2009	2010	2011	2012	2013
9.50	11.60	14.17	17.31	21.14	25.82	31.54	38.52	47.05
	7.78	9.50	11.60	14.17	17.31	21.14	25.82	31.54
		6.37	7.78	9.50	11.60	14.17	17.31	21.14
			5.21	6.37	7.78	9.50	11.60	14.17
				4.27	5.21	6.37	7.78	9.50
					3.49	4.27	5.21	6.37
						2.86	3.49	4.27
							2	2.86
								1.92

PROBABILITY LATTICE

t_n

2005	2006	2007	2008	2009	2010	2011	2012	2013
1.00	0.72	0.52	0.38	0.27	0.20	0.14	0.10	0.07
	0.28	0.40	0.43	0.42	0.38	0.33	0.28	0.23
		0.08	0.17	0.24	0.29	0.32	0.32	0.31
			0.02	0.06	0.11	0.16	0.20	0.24
				0.01	0.02	0.05	0.08	0.11
					0.00	0.01	0.02	0.04
						0.00	0.00	0.01
							0.00	0.00
								0.00

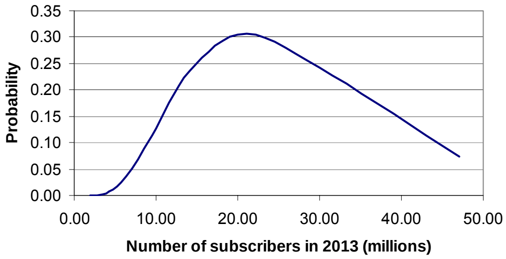


Figure 6.24. A preliminary outcome lattice, probability lattice and the form of a probability distribution function for the Basic package submarket in year 2013, with α =11.9 and σ =20%

In the next step, the lattice of the number of subscribers is being transformed into the lattice of revenues. The revenue function is a complicated function of the type of service package, number of subscribers per package, charged premium, number of on-board transponders, number of leased transponders, lease price per year, market uncertainty for each package, and transponder leasing market uncertainty. We define the revenue function for the DirecTV-8 satellite as follows:

$$\Re^{t_j,k}{}_{total} = \sum_{i=basic,\,premium1,\,premium2,\,international} \Re_i\left(n_i, x_i, m_i, l_i, R_i, R_{\min,i}, p_i(\alpha,\sigma), r, \delta t\right) \qquad (6.9)$$

where

t_j = decision points in time, $j=0,1,\ldots,n$

k = state at each stage

n_i = number of subscribers in the first period for each market

x_i = premium charged, $

m_i = number of transponders on board the spacecraft

l_i = number of transponders for lease

R_i = lease price, \$/year

$R_{\min,i}$ = minimum acceptable revenue for DirecTV-8 satellite (for revenues less than this value, some number of transponders are leased for extra revenue generation)

$p_i(\alpha,\sigma)$= probability distribution for each period as a function of drift and volatility

r = discount rate

δt = time steps, year

The most important driver of revenue is the number of on-board transponders. The increase in the number of on-board transponders creates the possibility of broadcasting more digital channels and therefore increasing the number of channels for each of the four major packages, particularly for the basic package, which has the greatest number of subscribers. DirecTV has a plan to increase the amount of local channel coverage to 1500 channels. The extra transponders can be used to fulfill this goal. More channels in each package translate to an increase in attractiveness of the DirecTV services; therefore, DirecTV should attracts subscribers from its rivals, such as other cable companies. The result is an increase in DirecTV's growth trend, with the increase in the number of transponders. The growth trend is modeled to have an S-shaped form, considering saturation of attractiveness after a specific number of channels.

The next important driver of revenue is leasing some number of extra transponders. Here we create the option of leasing some number of transponders after 2008 and 2010 if the market does not materialize as predicted. Therefore, in such a situation, the decision-maker has the option of limiting the growth of the number of channels in each package and leasing the extra transponder capacity. The decision can be made after the specified year in each of the nodes (states), based on the generated revenue.

In order to calculate the total revenue, we start from the last period in the revenue tree and use a backward iterative process and dynamic programming techniques to calculate the total revenue generated by the DirecTV-8 satellite. The reader is recommended to consult the details of the backward iterative process and dynamic programming in

Trigeorgis (1996). The generated revenue is calculated by our model over the period of 2006-2013 for DirecTV-8 satellites for each of the defined alternatives and the baseline case.

For calculation of the extra revenue from upgrading the software, we use decision tree analysis. The existing uncertainty is related to the digital compression algorithms. The decision tree model can be seen in Figure 6.25. We assume that in year 2008, digital compression technique advances enable the on-board transponders to broadcast more than the number of channels per transponder possible today. The current number of channels per transponder is γ, and the future numbers of transponders are λ, ψ, and η with probabilities *p, q,* and *1-p-q,* respectively. Hence,

$$\text{\# of channels per transponder after software upgrade} = \lambda p + \psi q + \eta(1 - p - q) \qquad (6.10)$$

The software upgrade enables DirecTV-8 satellite to broadcast more channels per transponder, and therefore increases the revenue of the satellite when it is combined and linked concurrently to the binomial lattice model of the market.

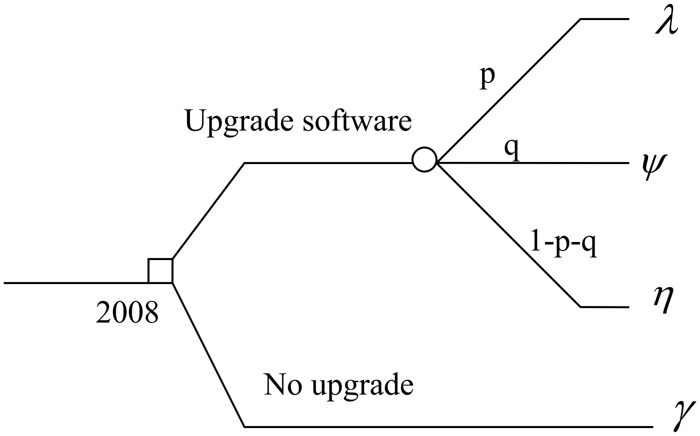


Figure 6.25. Decision tree for software upgrade

In the next step, we calculate the revenues for the baseline case and all defined alternatives. The extra benefit (revenue) associated with each alternative is calculated by subtracting the alternative's revenue from baseline revenues. The extra revenue is used in flexibility tradespace.

Cost Model

The cost model consists of several parts, which include the original satellite cost, cost of extra on-board transponders, cost of modification of satellite to accommodate extra on-board transponders, cost of software upgrade, cost of operation, and cost of launch. The main source of our cost model is Cost Estimating Relationships (CER) from Space Mission Analysis and Design (SMAD 1999) and DirecTV's 2004 annual report. A schematic of our cost model can be seen in Figure 6.26.

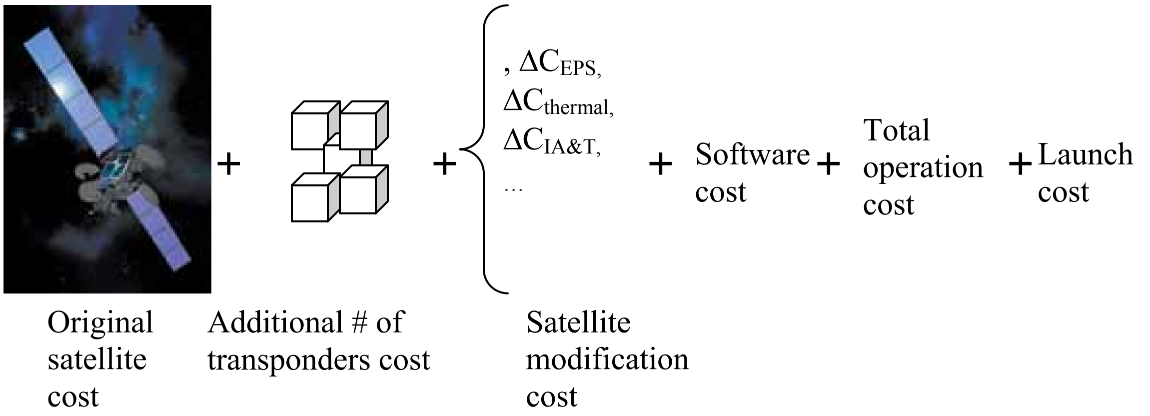


Figure 6.26. A schematic of the DirecTV-8 cost model

In general, we can present DirecTV-8 satellite cost as follows:

$$C_{DirecTV-8} = C_{sat} + \Delta C_{transponders} + \Delta C_{EPS} + \Delta C_{thermal} + \Delta C_{IA\&T} + C_{launch} + \Delta C_{SW} + \sum_{i=1}^{8} \frac{C_{i,operation}}{(1+r)^i} \tag{6.11}$$

where

$C_{DirecTV-8}$ = Total cost of DirecTV-8

C_{sat} = Original cost of DirecTV-8

$\Delta C_{transponders}$ = Cost of extra number of transponders installed on DirecTV-8

ΔC_{EPS} = Extra cost of solar panel, batteries, electrical system

$\Delta C_{thermal}$ = extra cost of thermal system

$\Delta C_{IA\&T}$ = Extra cost of integration, assembly, and test

C_{launch} = Launch cost

ΔC_{SW} = Software upgrading cost

$C_{i,operation}$ = Operation cost in year *i*.

The source of the satellite cost and operation cost are from DirecTV's annual report (2004). The original satellite cost consists of construction costs, launch costs, launch insurance, direct development costs, and capitalized interest. Capitalized satellite costs represent satellites under construction and the costs of successful satellite launches. Other costs are calculated from Tables 20.4, 20.5 and 20.13 in SMAD (1999) adjusted for FY2005. The cost of operation is considered to fluctuate randomly, is modeled with binomial lattice, and is calculated over the period of our study (from 2006 to 2013).

The baseline case satellite cost consists of satellite, launch, and operation cost. For each alternative (depending on the number of extra inserted transponders or the software upgrade), the cost of transponders, extra solar panel, batteries, electrical system, thermal control, integration, assembly & test (IA&T), extra operation, and software cost are added to the baseline case in order to create the cost of the alternatives.

Flexibility Tradespace Exploration and Results

In the last step of the 6E flexibility framework, we create a flexibility tradespace and compare the flexibility of each defined alternative to the baseline case. Using the data from the previous section (cost model), we compare the amount of benefit (revenue) versus the associated cost of each alternative. An example of such tradespace created by data from DirecTV-8's baseline and alternatives can be seen in Figure 6.27.

It should be noted that one of the most important factors in shaping such a tradespace is how we formulate and choose the alternative sets. A decision maker creates the alternatives, which may be a selected set of alternatives for achieving a specific type of flexibility in a system. Here, the tradespace is not an exhaustive one. It can accept new sets of alternatives and become more complete. All suggested alternatives are compared against the baseline case.

One of the most important facts about the flexibility tradespace is that it shows the *Cumulative probabilistic extra costs and revenues (benefits) over a period of study*. The extra costs and revenues shown on each axis are representative of cumulative and probabilistic costs and benefits over a period of 8 years (2006-2014) for the DirecTV-8 satellite baseline case.

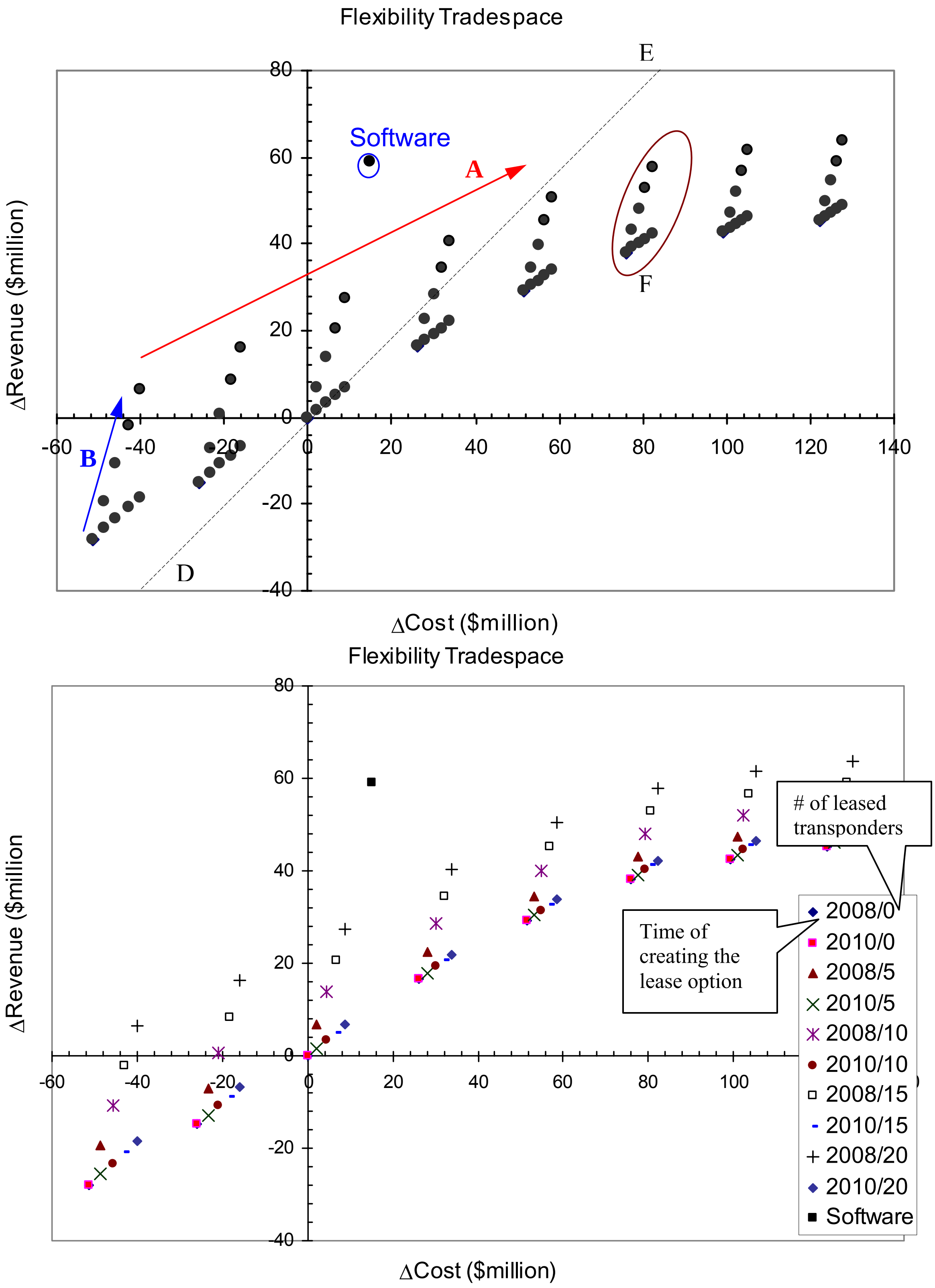


Figure 6.27. Flexibility tradespace for DirecTV-8 capacity expansion

Figure 6.27 compares 80 different alternatives against the baseline case. The method for constructing the alternatives is described in the previous section. The alternatives are spread out over three quadrants of the plane, which is accidental, based on the choice of our baseline case. The assumptions for this case study and a sample of calculations is presented in the Appendix.

The alternative of software upgrade, which is a highly flexible, can be seen in Figure 6.27. The cost of software upgrade is assumed \$20 million based on the DirecTV Group annual report as a portion of the total cost of software upgrade of this company. The cost of software upgrade is low in comparison with designing more transponders for the satellite, but the benefits are far more than just adding a number of transponders. With investment in R&D for digital compression techniques, DirecTV can send a larger number of channels per transponder, which increases the channel delivery capacity on board of a single DirecTV satellite. However, the cost is much less than a change of original design, extra satellite mass, and extra launch cost. The alternative of software upgrading can also be combined with different numbers of transponders to boost the revenue generation of the satellite.

As can be seen in Figure 6.27, the alternatives are grouped in several clusters. The ellipse *F* shows one group of alternatives, which is associated with a design of 44 Ku-band transponders on DirecTV-8 satellite. Arrow *A* shows the direction of increase in the # of installed Ku-band transponders on-board DirecTV-8 satellite. Within each cluster of alternatives, the option of leasing creates flexibility and a large benefit. As can be seen in each cluster, leasing a larger number of transponders in earlier years creates the largest amount of revenue. Arrow *B* shows the direction of increase in the number of leased transponders within each cluster of alternatives.

The tradespace in Figure 6.27 is divided to two parts by *DE* line. The *DE* line determines the cost-effective alternatives from the non-cost-effective alternatives. The alternatives located in the upper left side of the line are the more flexible ones and they create more revenue in comparison to their associated cost. Therefore, the net value of the alternatives located in the left side of *DE* is positive, and the larger the value of each alternative, the more flexible the alternative.

Figure 6.28 shows only two series of alternatives with different numbers of transponders. The first series are the alternatives that are created by changing the number of on-board transponders and the second series consists of the first series designs plus having the option of leasing up to 20 transponders in year 2008 if the market does not show any growth from the current number of subscribers. The alternative *A* shows a modified direcTV-8 satellite with 24 transponders and no leasing in its lifetime. The alternative *B* is the same satellite design with 24 transponders, but it has the option of leasing 20 of its transponders if the number of subscribers goes down from the current situation. The alternative *C* is a DirecTV-8 design with 52 transponders and the option to lease 10 of its transponders if the market is down. As can be seen from the data trend in Figure 6.28, with the increase of number of transponders, the extra cost of putting more transponders on-board also increases but after a certain number of transponders, the revenue generated grows of a lower rate than the cost.

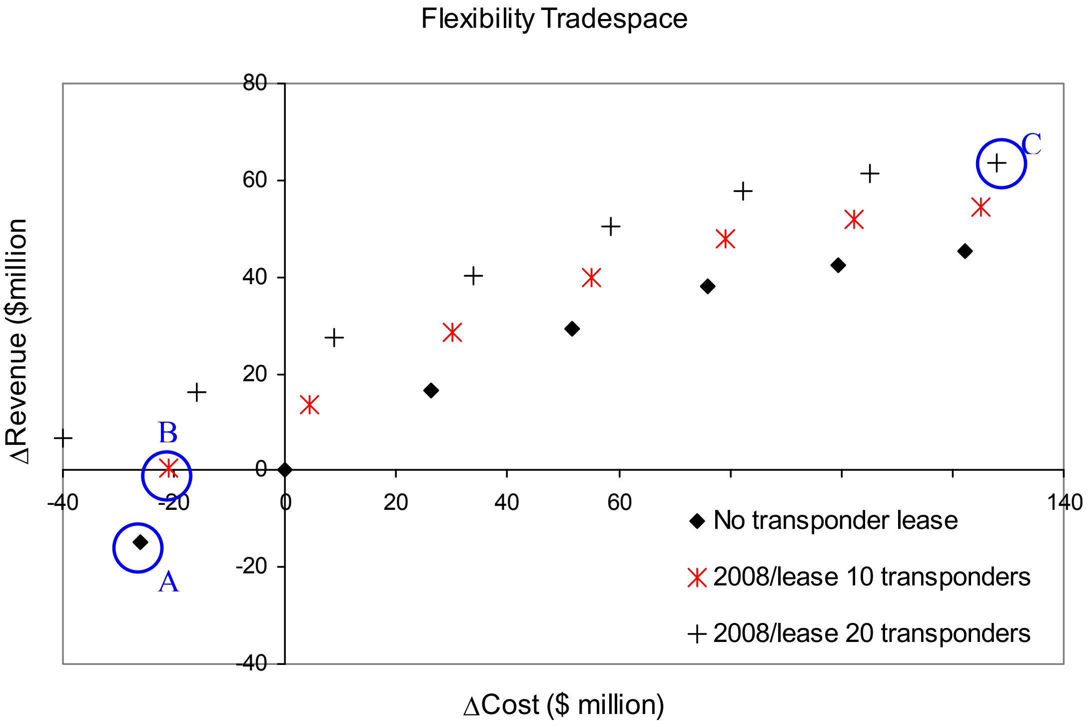


Figure 6.28. Demonstration of a subset of alternatives

It should be noted that all the points in flexibility tradespace are representatives of the *expected costs and revenues* of alternatives. There is an uncertainty bubble surrounding each of these alternatives. The uncertainty bubble is stretched in alignment with the extra revenue axis and narrow in alignment with the extra cost axis. The reason for this behavior is difference in uncertainty of the revenue and cost. The revenue of DirecTV-8 is strongly coupled with subscriber market uncertainty; however, the major percentage of cost is design, manufacturing, and launch cost, which is bounded within a known range and does not follow the subscriber market uncertainty. The only part of cost relevant to subscriber uncertainty is the operation cost of DirecTV-8, which increases with the number of on-board transponders.

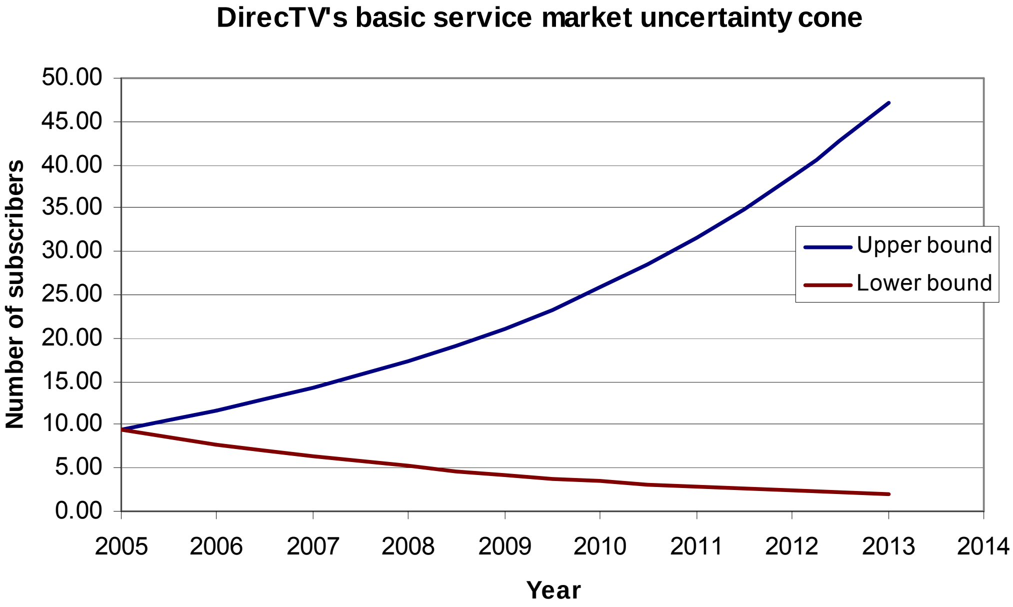


Figure 6.29. Market uncertainty cone (95% confidence) for DirecTV's basic service

Figure 2.29 shows the subscriber market uncertainty cone for the Basic package market. As can be seen in the figure, starting from the current existing market (2005), the uncertainty of the market going up or down increases and creates an uncertainty cone. Similar patterns with different market drift and volatility can be observed for the markets for Premium 1, Premium 2 and International package.

In summary, the following interesting observations can be made from case study #1:

- Software upgrades can create a large value of flexibility in a space system.
- Leasing a number of unused transponders can create a large value of flexibility in telecommunication satellites.

- The earlier the possibility of leasing transponder, the more flexible the leasing alternative becomes.
- Installing a larger number of transponders on a satellite can potentially create more revenue, but it also associated with a large upfront cost.
- If a decision-maker is concerned with capacity expansion of his/her satellite, market driven uncertainties have a more dominant effect in the value of flexibility than uncertainties in transponder technology development.

6.8.2 Case Study 2: DirecTV Fleet Mix of Service Flexibility

In this section, we look at another case study, which involves a fleet of DirecTV's satellites. In this second study, we will look at the flexibility of DirecTV's satellite fleet with respect to providing a *mix of services* to its customers. Currently, DirecTV is a provider of satellite TV services to its customers through a fleet of satellites, which provide this service through Ku-band transponders. DirecTV's near-future satellites, which are planned to be launched from 2005 to 2007, will utilize Ka-band transponders to provide HDTV and digital channels over the continental U.S. The ownership of a large number of Ka-band transponders on board the future DirecTV satellite fleet provides the opportunity also to provide broadband services to its customers. In case study #2, we study some different alternatives that can create a mix of service flexibility in the system. We apply the 6E flexibility framework step by step to create a flexibility tradespace. A summary of the 6E framework can be seen in Figure 6.16.

Problem Definition

In the first step of the 6E flexibility framework, we define the aspects of flexibility. In case study #2, we assume that the decision-maker is concerned with being able to provide a mix of TV and broadband services, if the satellite broadband market materializes. The chosen system boundary contains three of the DirecTV satellite fleet, including DirecTV-8, DirecTV-11, and Spaceway 2, respectively. Except for DirecTV-8, which has only 4 Ka-band transponders on board, the satellites have almost 40 Ka-band transponders each. The chosen time window of study is 15 years, starting from 2006.

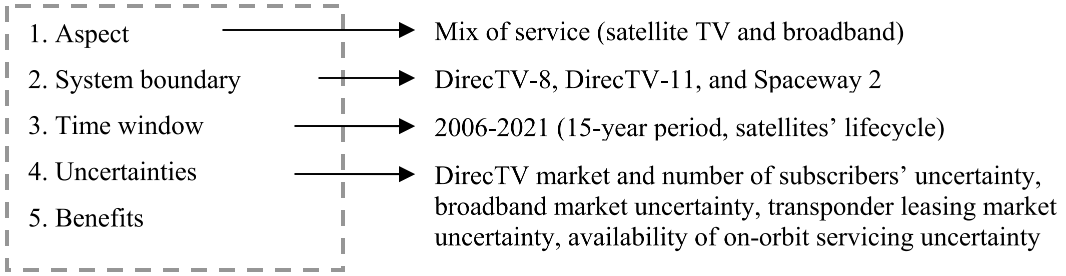


Figure 6.30. Problem definition for DirecTV case study #2

There are several major types of uncertainties involved in case study #2. These major types of uncertainty include the DirecTV market and number of subscribers uncertainty, broadband market uncertainty, transponder leasing market uncertainty, availability of on-orbit servicing uncertainty, and the technical uncertainty relevant to transponder efficiency and design. The above-mentioned uncertainties have a critical role in creating the DirecTV fleet revenue model for case study #2.

The dynamics of revenue generation of DirecTV case study #2 are shown in Figure 6.31. A Ka-band transponder is inherently capable of providing HDTV and broadband services. We assume that the existence of some numbers of Ka-band transponders enables DirecTV's management to decide on providing a mix of two services to DirecTV's customers if that is more profitable than the status quo. Therefore, a number of Ka-band transponders may be allocated for broadband services. DirecTV's management is also able to lease some number of its Ka-band transponders. Therefore, DirecTV's revenue will be a sum of its revenues from TV, broadband, and leasing services.

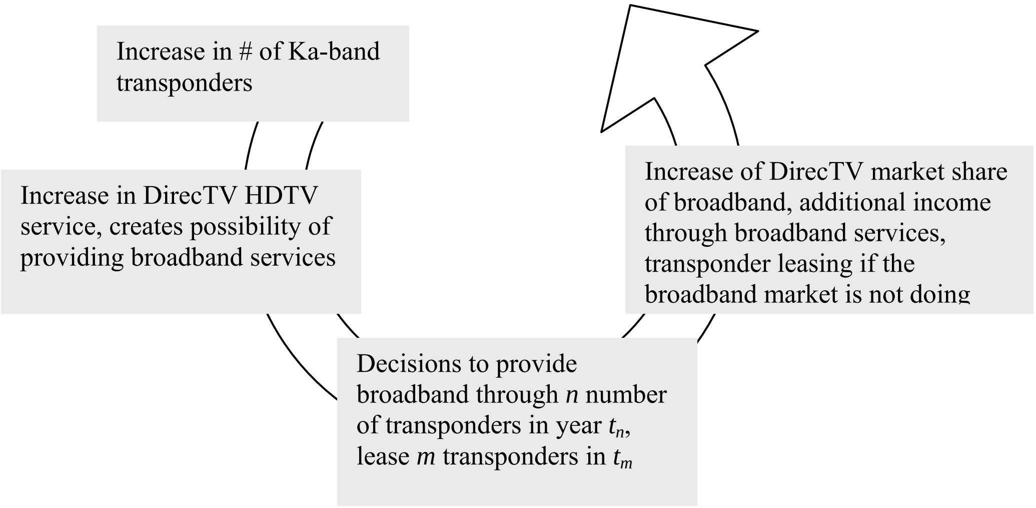


Figure 6.31. DirecTV's fleet revenue as a function of number of Ka-band transponders for case study #2

Currently, most of the DirecTV satellites in our fleet case study #2 are planned for HDTV uses. According to the forecasts by Futron, the direct broadcast services in the near future will have the largest rate of growth, which can be seen in Figure 6.32. In comparison to video applications, broadband service through satellites is predicted to have a slower growth rate than voice services. The forecasts for future trends of GEO communication satellites show a dramatic increase in use of Ka-band transponders on board telecommunication satellites (Futron 2003A).

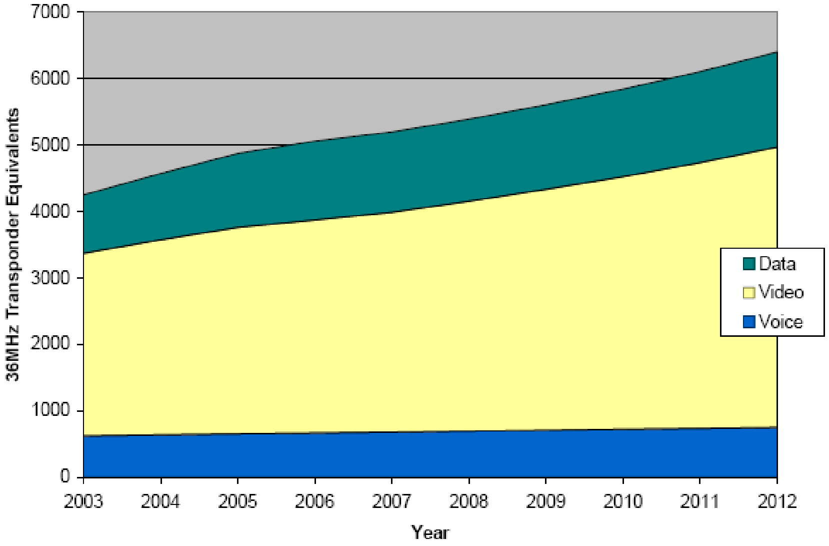


Figure 6.32. A forecast of data, video, and voice through satellite by Futron (Futron 2003A)

Creating a Baseline and Alternatives

In the next step of the framework, we suggest defining a set of alternatives, which may create more flexibility with respect to providing a mix of services. First, we create a baseline case, which consists of DirecTV-8, DirecTV-11, and Spaceway 2 satellites with n_{total} number of on-board Ka-band transponders. We assume that the only service provided by the baseline case is TV and video services. The alternative set 1 is created, based on allocating n_{BB} number of Ka-band transponders to broadband services in year t_{BB}. The remaining transponders (n_{TV}) are allocated to TV broadcasting. The alternative set 2 is designed based on upgrading the on-board Ka-band transponders in year t_{OOS} through on-orbit servicing. We assume that the on-orbit servicing on the DirecTV fleet will be performed in 2010 or 2016, with a probability distribution relevant to existence of on-orbit servicing in the two years mentioned. Upgrading the on-board transponders creates the possibility for a higher capacity of service, and hence more revenue.

The alternative set 3 is created by initially installing more Ka-band transponders on board the fleet. We consider allocating n_{extra} number of transponders of broadband services in year 2006. The alternative set 4 considers leasing n_{LE} number of transponders from alternative set 3. Therefore, in this alternative set, we allocate n_{BB} transponders to broadband, n_{LE} to leasing, and $n_{total} + n_{extra} - n_{BB} - n_{LE}$ to TV broadcasting services. The alternative 5 envisages a software upgrade, which enables transfer of larger amounts of data efficiently. The 5th alternative can be combined with any of the other alternatives. Figure 6.33 shows a brief description of alternative sets and the baseline case.

6. Create a baseline case and possible alternatives based on degree of access

Baseline: A fleet of DirecTV-8, DirecTV-11, and Spaceway 2 original designs, with a total of n_{total} Ka-band transponders on board

Alternative set 1: original design of the fleet, providing a mix of HDTV and broadband services, using n_{BB} number of transponders in year t_{BB}

Alternative set 2: in case of existence of a large DirecTV market and availability of on-orbit servicing in year t_{OOS} to upgrade the on board Ka-band transponders

Alternative set 3: installation of more transponders in year 2006 on-board the satellite fleet and using a portion of them for providing broadband.

Alternative set 4: leasing n_{LE} number of transponders from alternative set 3

Alternative 5: using new software digital compression techniques in year t_{SW}

Figure 6.33. A set of alternatives and DirecTV's original fleet design as a baseline case

Technical Model

The technical model task is to modify the baseline case design of the satellite fleet to accommodate necessary changes for each alternative. The schematic of the technical model for case study #2 can be seen in Figure 6.34. The alternative set 1 and alternative 5 do not need any major design modifications. The alternative set 2 is associated with physical changes performed on the fleet's transponders and, therefore, uses the technical design model. The alternative sets 3 and 4 are associated with installing a larger number of Ka-band transponders on board, and therefore major changes in power, thermal control, mass and volume of the fleet. The relationships for power and mass modification of the fleet are similar to the calculations for case study #1.

Technical design model:

- A selection of Ka-band transponders
- New power requirement
- New thermal radiator design
- New solar panel and battery design
- Extra spacecraft bus modification
- Total mass calculation

Figure 6.34. Technical design model for the alternatives that need changes in the original DirecTV-8, DirecTV-11, and Spaceway 2 designs

Economic Evaluation Model

In the economic evaluation model, we choose a combination of evaluation methodologies based on the types of uncertainty of most importance. Here, the major types of uncertainty are market and technological uncertainty. The market uncertainty is divided into the following three submarket uncertainties:

- Direct to home TV broadcasting market uncertainty
- Broadband market uncertainty
- Transponder leasing market uncertainty

The technological uncertainties have a broad range, including uncertainty associated with the existence of on-orbit servicing, transponder technology advances uncertainty, software advances uncertainty, and uncertainty associated with advances in digital compression techniques. A brief description of the economic evaluation model can be seen in Figure 6.35.

Economic evaluation model:

- Evaluation methodology: decision analysis and real options with binomial lattice analysis
- Revenue in \$, $\Re$ (# of subscribers for TV service, premium charged for TV service, # of subscribers for broadband service, premium charged for broadband, # of leased transponders, transponder lease market uncertainty, transponder performance increase through on-orbit servicing, transponder performance increase through software, increase in volume of transferred data through digital compression techniques)
- Cost in \$, C (original fleet, $\Delta C_{transponder}$, ΔC_{EPS}, $\Delta C_{thermal}$, $\Delta C_{IA\&T}$, ΔC_{launch}, $\Delta C_{operation}$, $\Delta C_{software}$, $\Delta C_{on\text{-}orbit\ servicing}$)

Figure 6.35. Economic evaluation model for calculating the revenue and cost associated with each alternative

Revenue Model

The revenue generated by DirecTV's fleet in case study #2 is a complicated function of many variables, which are described in this section. First, we describe the basic modeling behind each uncertainty of importance to case study #2. Then we describe the way we extract the revenue from each model.

As we mentioned in the previous section, there are three major markets involved in case study #2. The most important market is DirecTV's television broadcasting market, which creates the major portion of DirecTV's revenue. The TV broadcasting market is modeled using a binomial lattice analysis using the following relationships:

$$\Delta Y = \sqrt{\sigma^2 \delta t + \left(\alpha - \frac{\sigma^2}{2}\right)^2 \delta t^2}$$

$$p = \frac{1}{2}\left(1 + \frac{\left(\alpha - \frac{\sigma^2}{2}\right)\delta t}{\Delta Y}\right)$$

where α is the expected drift, σ is the volatility, and δt is the time step of the simulation. For this case study, we consider α ranging from 5% to 6.5%, $\sigma = 20\%$, and time steps are one year, with a lattice which is constructed for a time window of 15 years. Figure 6.36 shows an example of such a lattice that models the uncertainty of the number of subscribers (million) from 2006 to 2021. It should be noted that we have created a market cap of 60 million subscribers for the discrete states with larger than 60 million subscribers. The probability distribution function of TV service subscribers in year 2021 can be seen in Figure 6.37.

2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00
	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	60.00	60.00	60.00	60.00	60.00	60.00	60.00
		9.32	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	60.00	60.00	60.00	60.00	60.00
			7.63	9.32	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	60.00	60.00	60.00
				6.25	7.63	9.32	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	60.00
					5.11	6.25	7.63	9.32	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15
						4.19	5.11	6.25	7.63	9.32	11.38	13.90	16.98	20.74	25.33	30.94
							3.43	4.19	5.11	6.25	7.63	9.32	11.38	13.90	16.98	20.74
								2.81	3.43	4.19	5.11	6.25	7.63	9.32	11.38	13.90
									2.30	2.81	3.43	4.19	5.11	6.25	7.63	9.32
										1.88	2.30	2.81	3.43	4.19	5.11	6.25
											1.54	1.88	2.30	2.81	3.43	4.19
												1.26	1.54	1.88	2.30	2.81
													1.03	1.26	1.54	1.88
														0.85	1.03	1.26
															0.69	0.85
																0.57

Figure 6.36. An example of binomial lattice model of number of subscribers for TV service

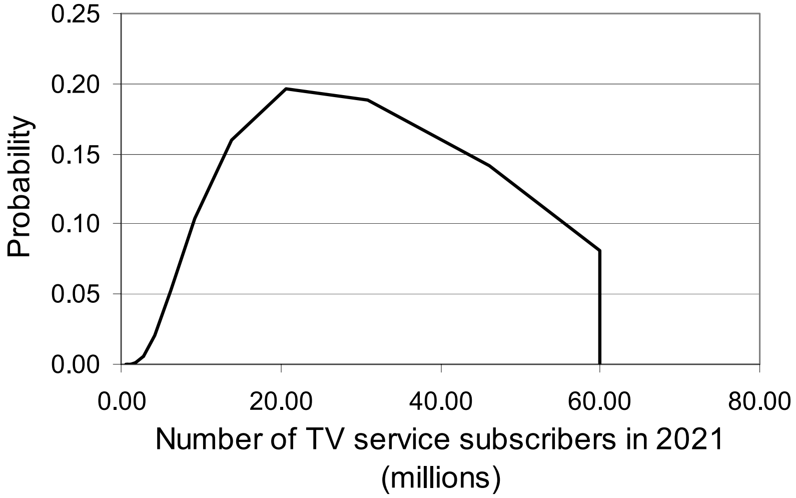


Figure 6.37. Probability distribution function for number of TV service subscribers in 2021

The other two important markets to be modeled are the broadband market and the transponder leasing market. The reader is referred to section 6.7 for description of the transponder leasing market. In our model, we assume that DirecTV is willing to lease a number of its transponders, ranging from zero to 40 transponders, which is considered as a very small portion of the total number of transponders being leased worldwide annually. Therefore, we consider that DirecTV is able to lease up to 40 of its transponders with a high probability if it decides to do so. The broadband market is also modeled through a binomial lattice. It should be noted that with our current state of technology, each Ka-band transponder could only accommodate 5 to 10 thousands of broadband subscribers. Therefore, allocating some number of transponders, e.g. 20 transponders, can accommodate at most 0.2 million broadband customers. Currently one transponder with a bandwidth of 36MHz is equal to six cable modem channels. The estimated current market for broadband via satellite is 15 million customers (Futron 2003B). Therefore, even allocating a large number of Ka-band transponders on board DirecTV's fleet would capture only a very small portion of the total broadband market in the U.S. However, it should be noted that with the current broadband satellite technology, companies dedicated only to broadband services, such as DirectPC and Echostar, have not been profitable.

The uncertainty associated with transponder and software technological advances, and on-orbit servicing availability is modeled using a decision tree analysis. Software and advances in digital compression techniques can improve the service and increase the amount of transferred data, increasing the number of subscribers and the revenue. The existence of an on-orbit servicing infrastructure also makes it possible to upgrade parts of digital transponders' technology and improve the performance of the transponders, and thereby increase the revenue of the DirecTV company.

In the next step, the lattice of the number of TV service subscribers is transformed to the lattice of revenues. The revenue function in each state and stage in the lattice is a complicated function of number of TV service subscribers, premium charged for TV service, number of broadband service subscribers, premium charged for broadband service, the year in which the decision to provide a mix of service is made, number of leased transponders, premium charged per leased transponder, the year in which the decision to lease a number of transponders is made, the minimum acceptable revenue for each state (some number of transponders are leased if the revenue is less than the minimum acceptable), number of additional installed transponders, improvement-of-service coefficient through software upgrading, the year the software upgrading is performed, improvement-of-service coefficient through on-orbit servicing, the year that on-orbit servicing is performed, and the probabilities associated with the software upgrade and on-orbit servicing availability. We can show the revenue function in each state and stage of the binomial lattice as the following function (the elements, which are not applicable to some states and stages, are considered to be dormant):

$$\Re^{t_j,k}{}_{total} = \Re_i\left(n_{TV}, n_{BB}, n_{LE}, n_{extra}, x_{TV}, x_{BB}, x_{LE}, t_{BB}, t_{LE}, t_{OOS}, t_{SW}, R_{\min}, \varphi_{OOS}, \varphi_{SW}, p_{OOS}, p_{SW}, p_i(\alpha,\sigma), r, \delta t\right) \tag{6.12}$$

where

n_{TV} = number of TV service subscribers

n_{BB} = number of broadband service subscribers

n_{LE} = number of leased transponders

n_{extra} = extra number of installed transponders on board fleet

x_{TV} = premium charged for TV service, \$

x_{BB} = premium charged for broadband service, \$

x_{LE} = premium charged for leasing service, \$

t_j = decision points in time, $j=0,1,\ldots,n$

t_{BB} = decision point in time for allocating a number of transponders to broadband

t_{LE} = decision point in time for allocating a number of transponders to leasing

t_{OOS} = decision point in time for performing on-orbit servicing

t_{SW} = decision point in time for software upgrade

k = state at each stage

$R_{\min}$ = minimum acceptable revenue for fleet (for revenues less than this value, some number of transponders are leased for extra revenue generation)

$p_i(\alpha,\sigma)$ = probability at each state and stage as a function of drift and volatility

φ_{OOS} = improvement-of-service coefficient through on-orbit servicing

φ_{SW} = improvement-of-service coefficient through software upgrading

p_{OOS} = probability distribution for on-orbit servicing in year t_{OOS}

p_{SW} = probability distribution for software upgrading in year t_{SW}

r = discount rate

δt = time steps, year

The revenue function presented in Formula 6.12 creates a value for revenue in each state for any stage. Depending on the alternative's definition, some or all parts of the revenue function can have active effect on calculation of revenue for that specific alternative. For example, in alternative set 1, the total number of on-board transponders remains constant (as in the baseline case), and the active variables are number of transponders allocated to broadband, decision years for launching a mix of broadband and TV services, premium charged per broadband and TV subscriber, probability associated with each state, etc., while the variables associated with on-orbit servicing, transponder leasing, software upgrading, and installing extra transponders remain dormant.

There are several other functions built into the revenue model. For example, one function translates the extra installed transponders to an increase in annual growth of the TV subscriber market, with consideration of TV market saturation. Another example is a function that translates allocating more transponders to broadband and leasing to decreases in amount and quality of TV service. Therefore, with increases of the percentage of transponders allocated to broadband and leasing, the revenue of the transponders allocated to TV service decreases gradually.

In order to calculate the total revenue, we start from the last period in the revenue tree for each defined alternative, and use a backward iterative process and dynamic programming techniques to calculate the total revenue generated by DirecTV's fleet. The reader is advised to consult the details of the backward iterative process and dynamic programming in Trigeorgis (1996). We calculate the generated revenue for the baseline case and each of the defined alternatives by applying our model over the period of 2006-2021 for DirecTV's fleet as defined in case study #2.

Cost Model

The cost model consists of several parts, which include the original cost of the satellites in the chosen fleet, the cost associated with installing extra transponders on board the fleet and the relevant modification costs (electrical power system, thermal, and integration and testing), software upgrading cost, operation cost, launch cost, and on-orbit servicing cost. Figure 6.38 shows the schematics of cost model used for case study #2.

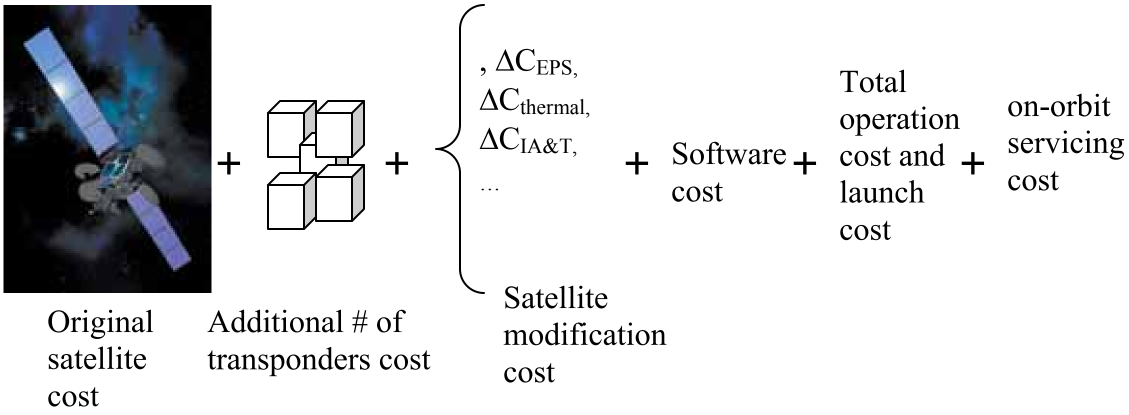


Figure 6.38. A schematic of DirecTV fleet cost model

In general, we can present DirecTV's fleet cost as follows:

$$C_{fleet} = C_{sat} + \Delta C_{transponders} + \Delta C_{EPS} + \Delta C_{thermal} + \Delta C_{IA\&T} + C_{launch} + \Delta C_{SW} + \sum_{i=1}^{8} \frac{C_{i,operation}}{(1+r)^i} + C_{OOS} \tag{6.11}$$

where

C_{fleet} = Total cost of DirecTV's fleet for case study #2

C_{sat} = Original cost of the fleet (cost of DirecTV-8, DirecTV-11, and Spaceway 2)

$\Delta C_{transponders}$ = Cost of extra number of transponders installed on fleet

ΔC_{EPS} = Extra cost of solar panel, batteries, electrical system

$\Delta C_{thermal}$ = extra cost of thermal system for the fleet

$\Delta C_{IA\&T}$ = Extra cost of integration, assembly and test

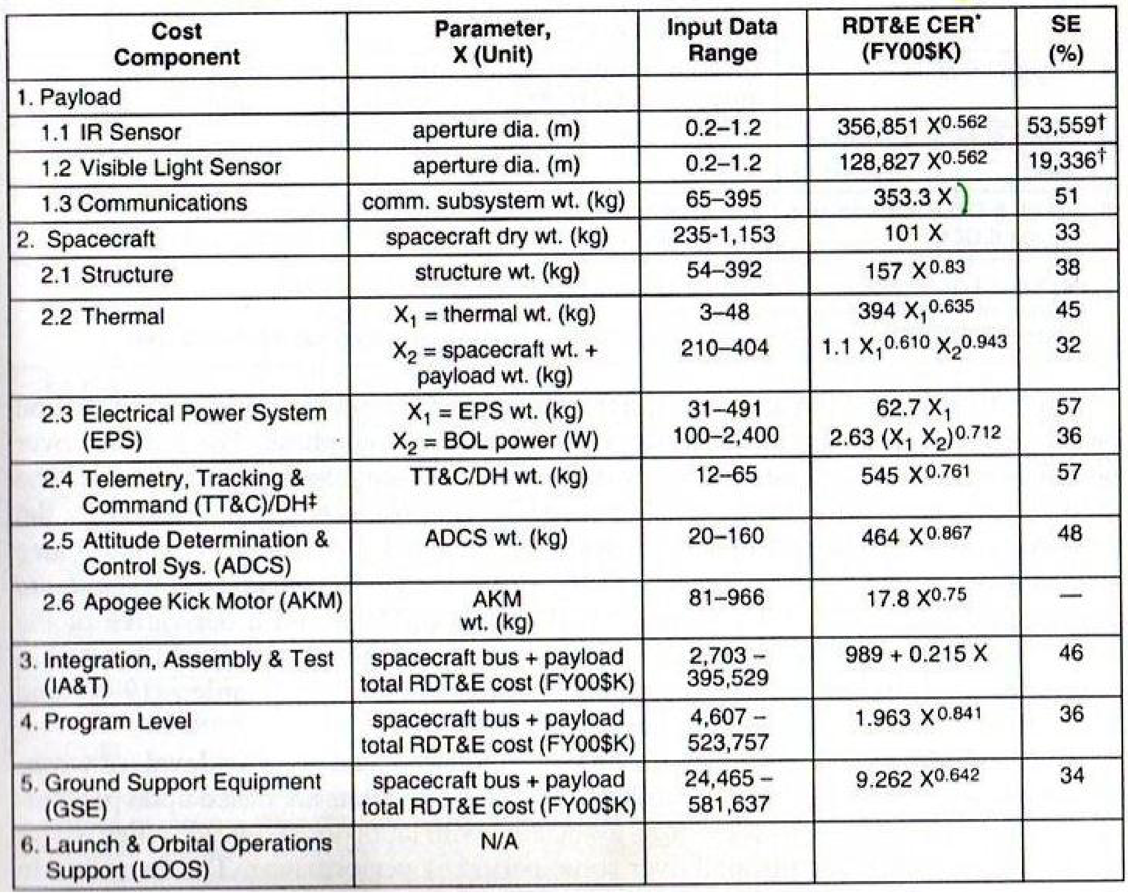
C_{launch} = Launch cost

$\Delta C_{software}$ = Software upgrading cost

$C_{i,operation}$ = Operation cost in year *i*.

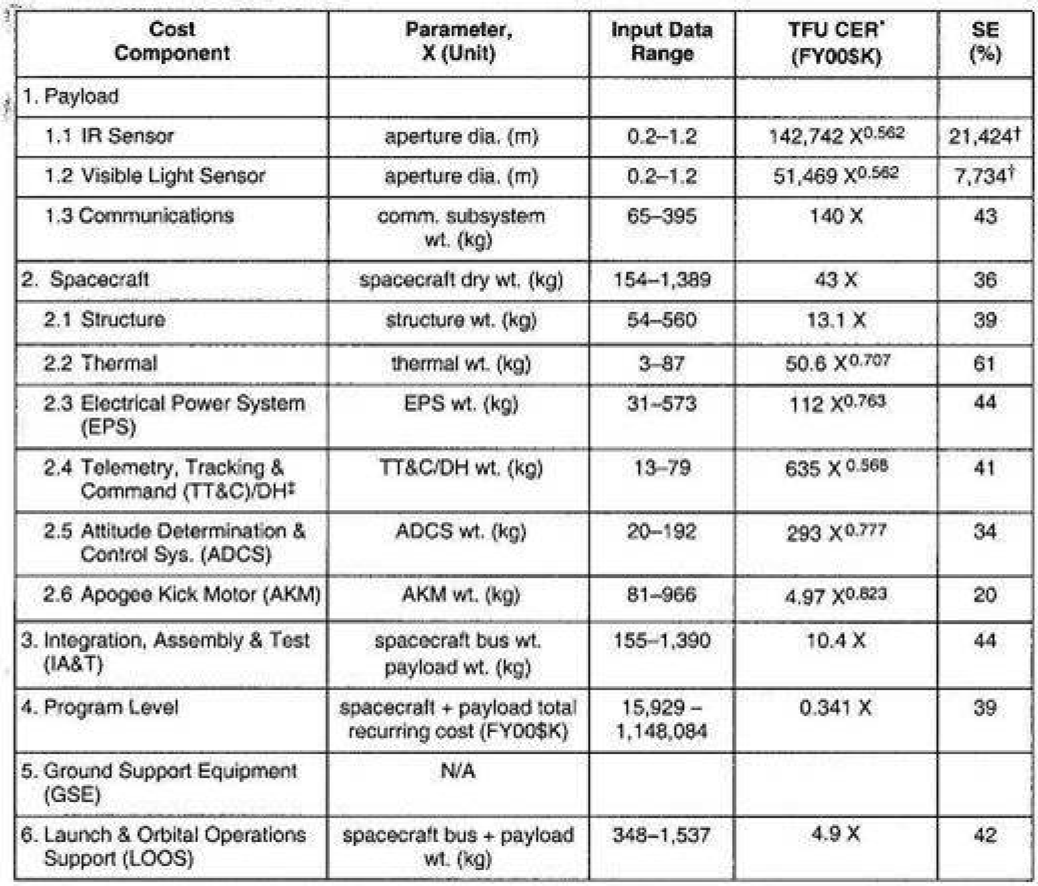
The source of the satellites' cost and operation cost are from DirecTV's annual report (2004). The original fleet cost consists of construction costs, launch costs, launch insurance, direct development costs, and capitalized interest. Other costs are calculated from Tables 6.10, 6.11 and 6.12 from SMAD (1999), adjusted for FY2005. The cost of operation is considered to fluctuate randomly, as a fraction of DirecTV's fleet revenue.

Table 6.10. CERs for estimating subsystem RDT&E cost (FY00$K) (taken from SMAD 1999)



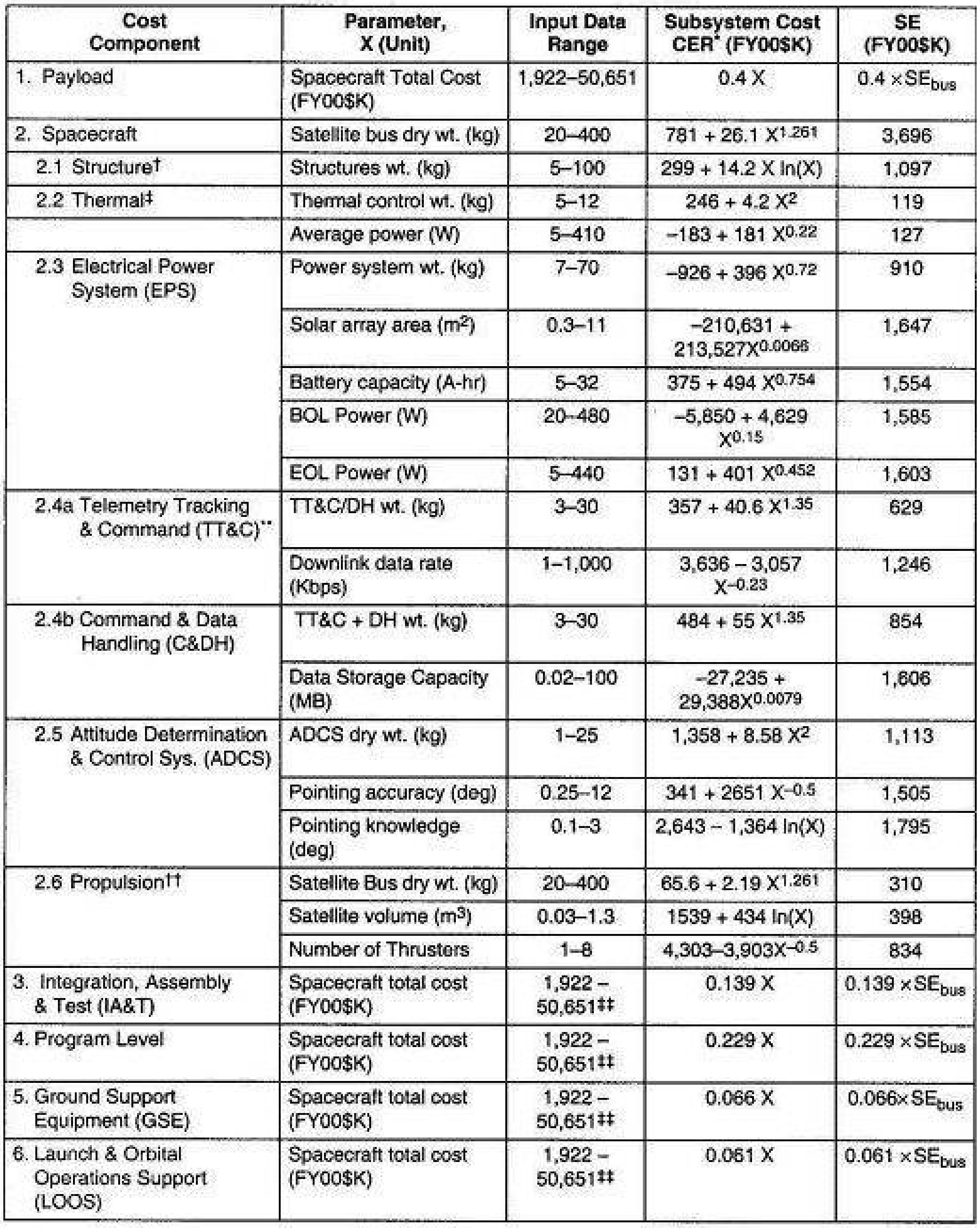
Cost Component	Parameter, X (Unit)	Input Data Range	RDT&E CER[*] (FY00$K)	SE (%)
1. Payload				
1.1 IR Sensor	aperture dia. (m)	0.2–1.2	$356{,}851\ X^{0.562}$	53,559[†]
1.2 Visible Light Sensor	aperture dia. (m)	0.2–1.2	$128{,}827\ X^{0.562}$	19,336[†]
1.3 Communications	comm. subsystem wt. (kg)	65–395	$353.3\ X$	51
2. Spacecraft	spacecraft dry wt. (kg)	235-1,153	$101\ X$	33
2.1 Structure	structure wt. (kg)	54–392	$157\ X^{0.83}$	38
2.2 Thermal	X_1 = thermal wt. (kg) X_2 = spacecraft wt. + payload wt. (kg)	3–48 210–404	$394\ X_1^{0.635}$ $1.1\ X_1^{0.610}\ X_2^{0.943}$	45 32
2.3 Electrical Power System (EPS)	X_1 = EPS wt. (kg) X_2 = BOL power (W)	31–491 100–2,400	$62.7\ X_1$ $2.63\ (X_1\ X_2)^{0.712}$	57 36
2.4 Telemetry, Tracking & Command (TT&C)/DH[‡]	TT&C/DH wt. (kg)	12–65	$545\ X^{0.761}$	57
2.5 Attitude Determination & Control Sys. (ADCS)	ADCS wt. (kg)	20–160	$464\ X^{0.867}$	48
2.6 Apogee Kick Motor (AKM)	AKM wt. (kg)	81–966	$17.8\ X^{0.75}$	—
3. Integration, Assembly & Test (IA&T)	spacecraft bus + payload total RDT&E cost (FY00$K)	2,703 – 395,529	$989 + 0.215\ X$	46
4. Program Level	spacecraft bus + payload total RDT&E cost (FY00$K)	4,607 – 523,757	$1.963\ X^{0.841}$	36
5. Ground Support Equipment (GSE)	spacecraft bus + payload total RDT&E cost (FY00$K)	24,465 – 581,637	$9.262\ X^{0.642}$	34
6. Launch & Orbital Operations Support (LOOS)	N/A			

Table 6.11. CERs for estimating subsystem theoretical first unit (TFU) cost (taken from SMAD 1999)



Cost Component	Parameter, X (Unit)	Input Data Range	TFU CER* (FY00$K)	SE (%)
1. Payload				
1.1 IR Sensor	aperture dia. (m)	0.2–1.2	142,742 $X^{0.562}$	21,424†
1.2 Visible Light Sensor	aperture dia. (m)	0.2–1.2	51,469 $X^{0.562}$	7,734†
1.3 Communications	comm. subsystem wt. (kg)	65–395	140 X	43
2. Spacecraft	spacecraft dry wt. (kg)	154–1,389	43 X	36
2.1 Structure	structure wt. (kg)	54–560	13.1 X	39
2.2 Thermal	thermal wt. (kg)	3–87	50.6 $X^{0.707}$	61
2.3 Electrical Power System (EPS)	EPS wt. (kg)	31–573	112 $X^{0.763}$	44
2.4 Telemetry, Tracking & Command (TT&C)/DH‡	TT&C/DH wt. (kg)	13–79	635 $X^{0.568}$	41
2.5 Attitude Determination & Control Sys. (ADCS)	ADCS wt. (kg)	20–192	293 $X^{0.777}$	34
2.6 Apogee Kick Motor (AKM)	AKM wt. (kg)	81–966	4.97 $X^{0.823}$	20
3. Integration, Assembly & Test (IA&T)	spacecraft bus wt. payload wt. (kg)	155–1,390	10.4 X	44
4. Program Level	spacecraft + payload total recurring cost (FY00$K)	15,929 – 1,148,084	0.341 X	39
5. Ground Support Equipment (GSE)	N/A			
6. Launch & Orbital Operations Support (LOOS)	spacecraft bus + payload wt. (kg)	348–1,537	4.9 X	42

Table 6.12. Cost estimating relationships for Earth-orbiting small satellites including RDT&E and theoretical first unit (Taken from SMAD 1999)



Cost Component	Parameter, X (Unit)	Input Data Range	Subsystem Cost CER* (FY00$K)	SE (FY00$K)
1. Payload	Spacecraft Total Cost (FY00$K)	1,922–50,651	0.4 X	$0.4 \times SE_{bus}$
2. Spacecraft	Satellite bus dry wt. (kg)	20–400	$781 + 26.1\ X^{1.261}$	3,696
2.1 Structure†	Structures wt. (kg)	5–100	$299 + 14.2\ X \ln(X)$	1,097
2.2 Thermal‡	Thermal control wt. (kg)	5–12	$246 + 4.2\ X^2$	119
	Average power (W)	5–410	$-183 + 181\ X^{0.22}$	127
2.3 Electrical Power System (EPS)	Power system wt. (kg)	7–70	$-926 + 396\ X^{0.72}$	910
	Solar array area (m²)	0.3–11	$-210{,}631 + 213{,}527X^{0.0066}$	1,647
	Battery capacity (A-hr)	5–32	$375 + 494\ X^{0.754}$	1,554
	BOL Power (W)	20–480	$-5{,}850 + 4{,}629\ X^{0.15}$	1,585
	EOL Power (W)	5–440	$131 + 401\ X^{0.452}$	1,603
2.4a Telemetry Tracking & Command (TT&C)**	TT&C/DH wt. (kg)	3–30	$357 + 40.6\ X^{1.35}$	629
	Downlink data rate (Kbps)	1–1,000	$3{,}636 - 3{,}057\ X^{-0.23}$	1,246
2.4b Command & Data Handling (C&DH)	TT&C + DH wt. (kg)	3–30	$484 + 55\ X^{1.35}$	854
	Data Storage Capacity (MB)	0.02–100	$-27{,}235 + 29{,}388X^{0.0079}$	1,606
2.5 Attitude Determination & Control Sys. (ADCS)	ADCS dry wt. (kg)	1–25	$1{,}358 + 8.58\ X^2$	1,113
	Pointing accuracy (deg)	0.25–12	$341 + 2651\ X^{-0.5}$	1,505
	Pointing knowledge (deg)	0.1–3	$2{,}643 - 1{,}364 \ln(X)$	1,795
2.6 Propulsion††	Satellite Bus dry wt. (kg)	20–400	$65.6 + 2.19\ X^{1.261}$	310
	Satellite volume (m³)	0.03–1.3	$1539 + 434 \ln(X)$	398
	Number of Thrusters	1–8	$4{,}303 - 3{,}903X^{-0.5}$	834
3. Integration, Assembly & Test (IA&T)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	0.139 X	$0.139 \times SE_{bus}$
4. Program Level	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	0.229 X	$0.229 \times SE_{bus}$
5. Ground Support Equipment (GSE)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	0.066 X	$0.066 \times SE_{bus}$
6. Launch & Orbital Operations Support (LOOS)	Spacecraft total cost (FY00$K)	1,922 – 50,651‡‡	0.061 X	$0.061 \times SE_{bus}$

The baseline case cost consists of satellite, launch, and operation costs for the chosen fleet. For each alternative (depending on the number of extra transponders, software upgrading, and on-orbit servicing), the cost of transponders, extra solar panels, batteries, electrical system, thermal control, integration, assembly & test (IA&T), extra operation, software cost, and on-orbit servicing cost are added to the baseline case in order to create the cost of the alternatives. The cost of on-orbit servicing is assumed to be $15M for upgrading digital components of Ka-band transponders and is suggested by on-orbit servicing provider. In the next section, each alternative with its associated extra revenue and cost is presented in a flexibility tradespace.

Flexibility Tradespace Exploration and Results

In this section, the results of Δrevenue and Δcost associated with each of the introduced alternatives are presented in a tradespace format. Figure 6.39 shows 97 different alternatives. A brief summary of the baseline and alternatives in Figure 6.39 is presented here.

Baseline: A fleet of DirecTV-8, DirecTV-11, and Spaceway 2 original designs, with a total of n_{total} Ka-band transponders on board. The position of the baseline case is at the cross section of the Δcost and Δrevenue axes (0,0).

Alternative set 1: original design of the fleet, plus providing a mix of HDTV and broadband services, using n_{BB} number of transponders in year t_{BB}. They are shown by three different signs in the figure, based on the year that the decision for allocating a percentage of baseline case transponders to broadband use is made. The decision years are 2010, 2014, and 2018.

Alternative set 2: in case of the existence of a large DirecTV market and availability of on-orbit servicing in year t_{OOS} upgrading the on-board Ka-band transponders. Two subsets of alternatives show the extra revenue generated by on-orbit servicing. The cost of performing on-orbit servicing is considered to be constant and offered by the provider of such service in the future.

Alternative set 3: installation of more transponders in year 2006 on-board the satellite fleet and using a portion of them for providing broadband. The number of extra transponders ranges from 0,2,…30 and four strings of data show if 0, 5, 10, or 15 of these transponders were allocated for broadband use.

Alternative set 4: leasing n_{LE} number of transponders for baseline case. The number of leased transponders ranges from 0,5,…,40.

Alternative 5: using new software digital compression techniques in year t_{SW} for baseline case.

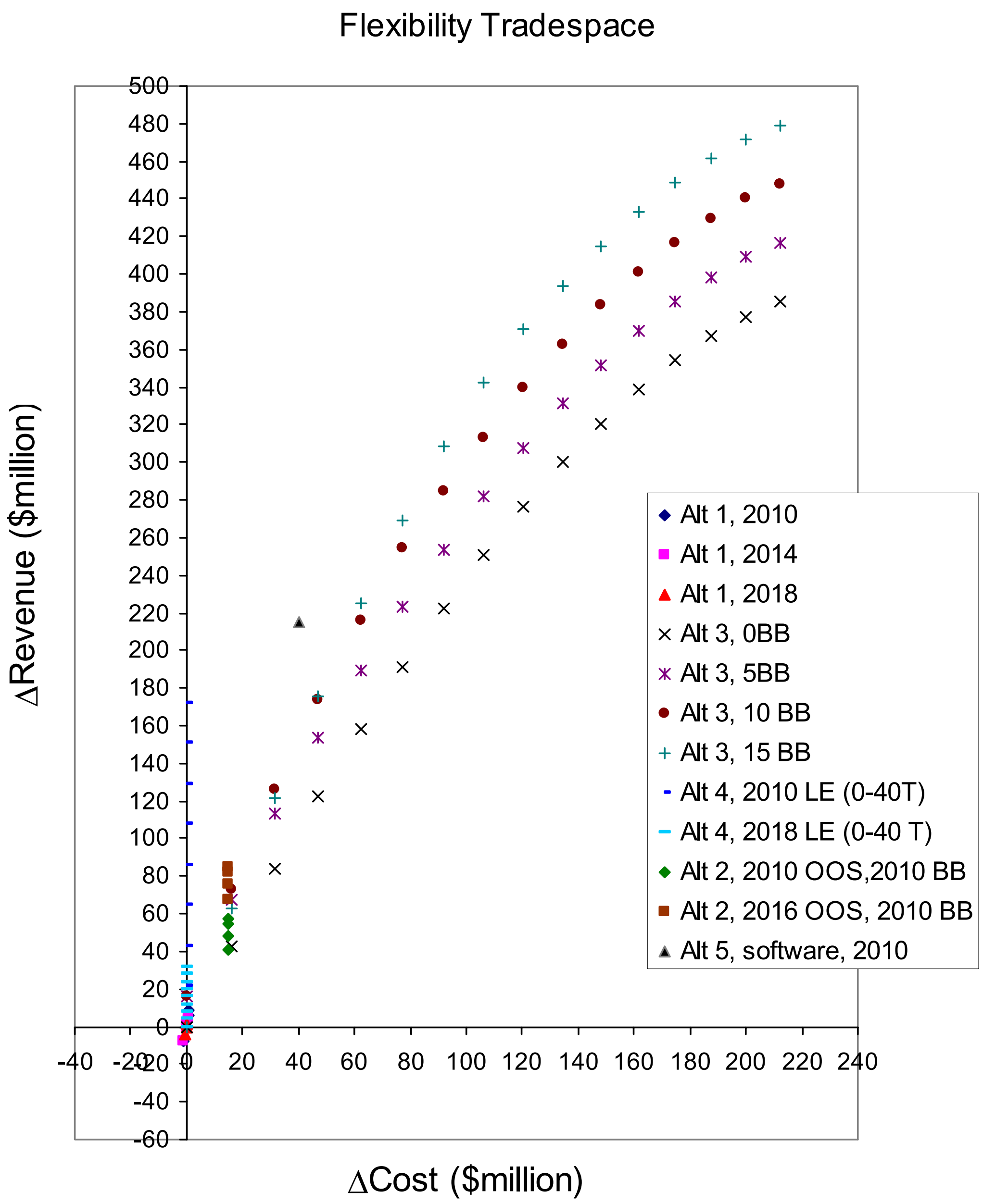
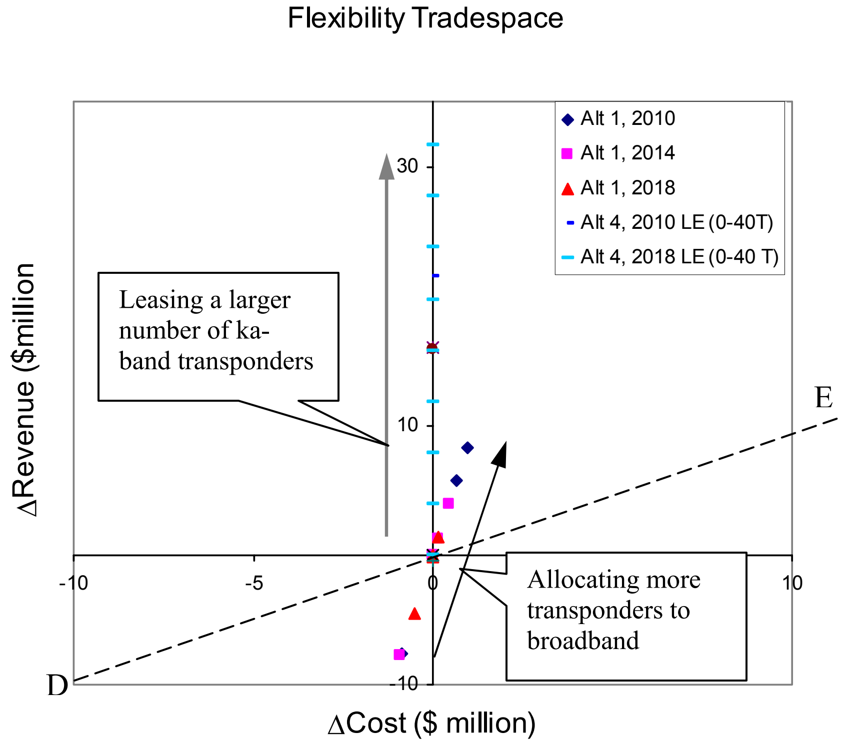


Figure 6.39. A flexibility tradespace for case study #2

The detailed study of subsets of flexibility tradespace is presented here.

Figure 6.40 shows a subset of flexibility tradespace, which contains the alternative sets 1 and 4. These two alternative sets are constructed based on the same technical specifications of the baseline case fleet. Alternative set 1 represents the allocation of 0, 5, 10, and 15 transponders of baseline case fleet to broadband services. The three subsets of the alternative 1 show three different decision times to allocate some number of transponders to broadband services. As can be seen in this figure, with an increase in the number of allocated transponders to broadband services, the revenue drops marginally. The cause of such behavior can be traced back to the current state of broadband satellite services, which is not very profitable. Currently, more revenue is generated by using a number of Ka-band transponders as TV service broadcasting in comparison with broadband services. But in case of existing extra numbers of transponders on board (more than the number needed to satisfy the TV market), some number of transponders can be used to generate more revenue through broadband.

The *DE* line separates the cost-effective alternatives from the non-cost-effective ones. The alternatives located above the *DE* line are cost effective and the farther we move from this line, the more flexible the alternatives.



Leasing a larger number of ka-band transponders

Allocating more transponders to broadband

Figure 6.40. Flexibility tradespace for alternatives 1 and 4

As can be seen in Figure 6.40, the business of leasing transponders can be more profitable and flexible in comparison with allocating some number of transponders to broadband. We can also see that if the decision to lease a number of transponders is made earlier in the fleet’s lifetime (2010 instead of 2018), more profit and flexibility can be achieved compared to the same number of leased transponders. Obviously, more leased transponders create more revenue, with consideration of a tradeoff, which is loosing a portion of DirecTV's television service revenue.

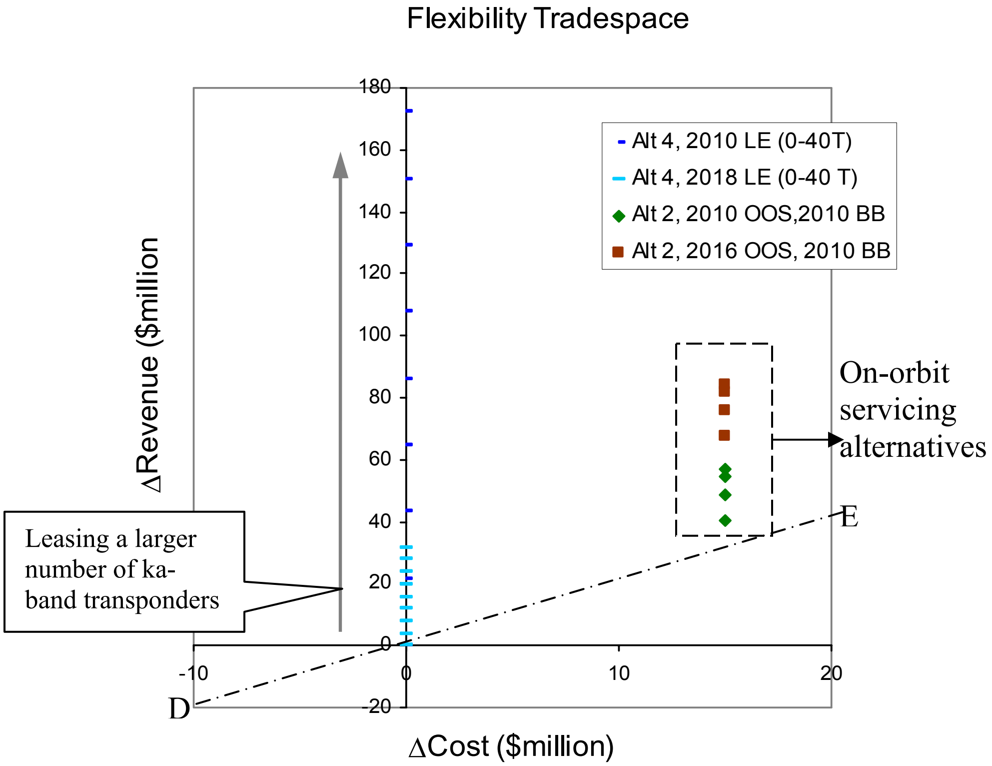


Figure 6.41. Flexibility tradespace for alternatives of leasing and on-orbit servicing on the baseline case design of the fleet

Figure 6.41 shows the on-orbit servicing and leasing alternatives for the baseline fleet design. As can be seen in the figure, if the leasing decision is made later (2018 instead of 2010), less revenue is generated for the same number of leased transponders. In general, leasing alternatives are flexible. The on-orbit servicing alternatives are presented in two subsets, based on the year on-orbit servicing is performed. Both of the on-orbit servicing alternatives also consider allocating a number of Ka-band transponders in 2010 to broadband services. The extra revenues generated by on-orbit servicing is larger if it is performed later (2016 instead of 2010) for two reasons. First, the probability of existence of an on-orbit servicing infrastructure is higher in 2016 in comparison to 2010, and the second reason traces back to the fact that the probability of more advanced transponder technologies with higher efficiency emerging is higher at a later time.

The *DE* line again separates the tradespace in Figure 6.41 to two parts. As can be seen form the figure, all alternative sets 2 and 4 are located above the *DE* line, or the cost effective region. Based on the price offered for servicing, on-orbit servicing can be a flexible and cost-effective alternative for a fleet of telecommunication satellite system. As before, the option to lease a number of on-board transponders is also very flexible and cost-effective and the flexibility of the alternatives increases with an increase in the number of leased transponders and with earlier starting points for the lease.

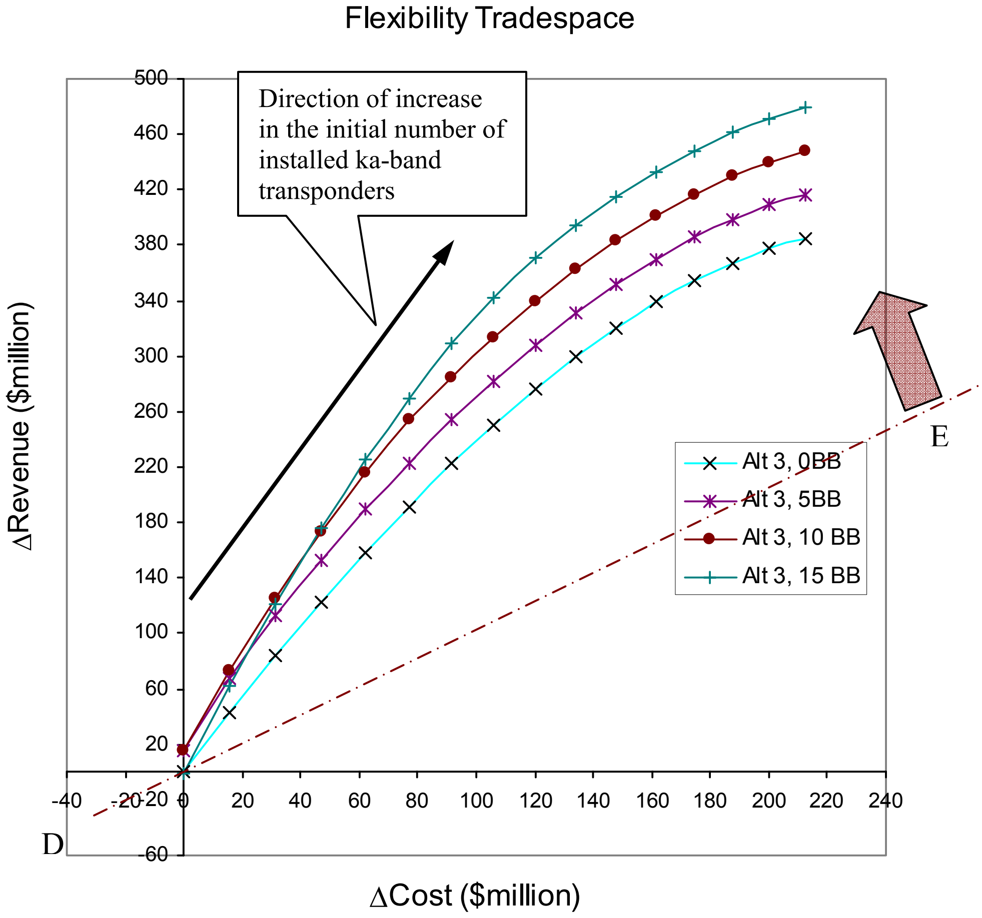


Figure 6.42. A flexibility tradespace for alternative sets 3

Figure 6.42 shows the alternative set 3 for different number of extra and leased transponders. As can be seen in the figure, with increase in the number of extra transponders, the extra revenue and cost increases. After a certain number of extra transponders, the extra revenue does not increase at the same amount as the extra cost increases. The major cause of this behavior is approaching the TV market saturation. The

DE line is also the cost effectiveness line, which divides the plane to two parts. As can be seen in the figure, all alternatives of set 3 are located in the cost effective region.
The alternative 5, or software upgrade, is of extreme importance. The software alternative can be seen in Figure 6.39. In some cases through software upgrade and better digital compression techniques, the extra gained benefits can be the same as installing a larger number of transponders on-board satellites. Usually, the cost of the software is less than the cost of installing more transponders, and that is the major reason for software being a more flexible option. It should be noted that the software upgrade and lease options, which have been studied for applications on baseline case only, can also be combined with any of the alternatives (e.g., alternative 3 plus software upgrade) to create a other sets of alternatives which are associated with higher revenues.

In summary, we make the following observations from the case study #2:

- With the current state of technology, mixing broadband via satellite and direct broadcasting TV is not a flexible option. Providing TV broadcasting services by a fleet of DirecTV satellites is a more profitable alternative in comparison with providing broadband via satellites through the same fleet.
- Leasing a number of on-board transponders is a viable and flexible alternative and the earlier the option is exercised, the higher its flexibility.
- Software upgrading is a flexible option that can be combined with other flexible alternatives to achieve the maximum flexibility in a space system.
- On-orbit servicing for upgrading the Ka-band transponders can be a flexible option depending on the offered price of servicing.

In general, a decision-maker is concerned with both technological and market uncertainty. From the viewpoint of technological uncertainty, more flexibility can be achieved through software upgrade and on-orbit servicing, while installing an initial larger number of transponders is not very promising. From the viewpoint of market uncertainty, flexibility can be built into the system through creating the option to lease from the early years of the fleet operation. On contrary, sharing the on-board transponders between the broadband and direct TV services decreases the flexibility of the system.

6.9 Summary

In this chapter, we applied our suggested 6E flexibility framework to two chosen case studies base on DirecTV Group. The major goal of these case studies is demonstration of the 6E flexibility framework. The two case studies are chosen from DirecTV Group, which is a commercial provider of satellite TV broadcasting service over the U.S. In first parts of this chapter, some information about the DirecTV, the structure, and its satellite assets are presented. Next, the DirecTV financial market and transponder leasing market is discussed. Each case study is presented next and the steps of the framework are applied. As the last step in each case study, the flexibility tradespace is created. Each of the alternatives is compared to the baseline case and the more flexible alternatives are identified.

It should be noted that this chapter includes only the commercial space system case studies. The generated revenue by each of these two DirecTV's case studies had a monetary form. In the next chapter, we demonstrate the 6E flexibility framework and its applications to a military space system, which possesses more than one type of benefit, and also in a non-monetary form.

References:

(Bass 2001)

"DirecTV: Forecasting diffusion of a new technology prior to product launch," Frank M Bass, Kent Gordon, Teresa L Ferguson, Mary Lou Githens. Interfaces. Linthicum: May/Jun 2001.Vol.31, Iss. 3; Part 2. pg. S82

(Chriss 1997)

Chriss, Neil, "Black-Scholes and beyond: option pricing models," Chicago, Irwin, c1997.

(DIR 2005)

http://www.directv.com/

(DIR 2004)

DirecTV's 2004 annual report, http://phx.corporate-ir.net/phoenix.zhtml?c=127160&p=irol-reports

(Evans 1999)

Evans, B. G., "Satellite communications systems," London, Peregrinus on behalf of the Institution of Electrical Engineers, 3rd edition, 1999.

(Fitch 2003)

Fitch, M., "The use of satellite for multimedia communications," BT Technology Journal, v 21, n 3, July 2003, p 90-101

(Futron 2003A)

"Global analysis of satellite transponder usage and coverage," Futron Corporation, October 2003, 7315 Wisconsin Avenue, Suite 900W, Bethesda, Maryland 20814, http://www.futron.com

(Futron 2003B)

"Satellite service demand: reloading the matrix," Futron Corporation, December 2003, 7315 Wisconsin Avenue, Suite 900W, Bethesda, Maryland 20814, http://www.futron.com

(Hull 1997)

Hull, John, "Options, futures, & other derivatives," Prentice Hall finance series, Upper Saddle River, N.J., Prentice Hall, c2003.

(Iida et al. 2003)

"Satellite communications in the 21st century: Trends and techniques," edited by Takashi Iida, Joseph N. Pelton, and Edward Ashford, Progress in astronautics and aeronautics ; v. 202, Published Reston, Va. : American Institute of Aeronautics and Astronautics, 2003.

(Lim 2004)
S. Lim, “Analytic Framework for Flexible Transponder Return on Investment,” 22nd AIAA International Communications Satellite Systems Conference and Exhibit 2004 (ICSSC), Monterey, California, May 9-12, 2004

(LOR 2005)
www.loral.com

(SMAD 1999)
Wertz, James R. and Larson, Wiley J., Space Mission Analysis and Design (SMAD), Microcosm Press and Kluwer Academic Publishing, 1999.

(Trigeorgis 1996)
Trigeorgis, Lenos, “Real options : managerial flexibility and strategy in resource allocation,” Cambridge, Mass. : MIT Press, c1996.

(Verma 2004)
S. Verma, “Advance Multimedia Satellite Systems,” 22nd AIAA International Communications Satellite Systems Conference and Exhibit 2004 (ICSSC), Monterey, California, May 9-12, 2004

(Verma et al. 2002)
S. Verma and E. Wiswell, “Next Generation Broadband Satellite Communication Systems,” 20th AIAA International Communication Satellite Systems Conference and Exhibit, Montreal, Quebec, May 12-15, 2002, AIAA-2002-1999

(Williams et al. 2003)
L. Williams, J. Dorsey, J. Foust, “GEO Communications Transponder Park: A New Concept for Direct Broadcast Services,” AIAA-2003-6316, AIAA Space 2003 Conference and Exposition, Long Beach, California, Sep. 23-25, 2003

Chapter 7

7. Measuring Different Aspects of Flexibility in Orbital Express Program

ORBITAL Express is a proposed program by DARPA[35] to provide an infrastructure in Earth's orbit to refuel, upgrade, repair, and relocate a number of specific client satellites. A system such as Orbital Express can potentially enable flexibility for its client satellite systems. In this chapter, we will look at two case studies involving the Orbital Express program and measure the flexibility created by the existence of such an infrastructure. The benefits generated by the Orbital Express program can appear in different forms and units other than dollars, which makes this case study an interesting application of our flexibility framework.

This chapter begins with a background on the Orbital Express program's on-orbit assets, and their functions and proceeds to introduce the case studies. We then apply our proposed 6E flexibility framework to the Orbital Express on-orbit assets, and measure the flexibility of this system with respect to the chosen aspect of interest.

---

[35] The Defense Advanced Research Projects Agency

7.1 The Orbital Express Program Background

The current state of the satellite industry is marked by very expensive satellites, redundancies in different satellite subsystems, and long and costly periods of development, integration, and testing. After a satellite is launched into the orbit, if any critical part fails, or the satellite ends up in a wrong orbit, or it runs out of fuel, there is only one solution: disposal.

The concept of on-orbit servicing has been proposed to address the following problems:

- Failure of critical parts on-board the satellite: Critical part failures may lead to early satellite retirement.
- Technology obsolescence: With the rapid pace of change, growth, and technological improvement in some satellite components, technological obsolescence during the operational lifetime of the satellite is very likely. For some technologies, particularly those related to communication and information processing the performance improvement follows Moore's law (doubling the capacity in a specific time interval, which is sometimes as little as a year).
- Limited satellite maneuverability: This problem is usually due to a fixed amount of on-board fuel, which limits satellite's mobility and lifetime. Currently the necessary fuel for the entire mission life (including all maneuvers, drag makeup, and end-of-life disposal) is launched with the satellite.

There are some exceptions such as Hubble space telescope, which has been serviced by Shuttle manned missions, and the capture and re-deployment of Leasat-3/Syncom-IV and Intelsat-VI. The above-mentioned missions involve very expensive shuttle missions with potentially risky Extra-Vehicular Activity (EVA) of the astronauts.

The Orbital Express program has been proposed by DARPA to fill the void of an autonomous robotic satellite servicing system. The task of the Orbital Express program is to refuel, repair, or upgrade parts on the client satellites. According to Dipprey et al. (2003), the benefits of on-orbit refueling are categorized to reduced launch weight, life extension, enhanced delta V budget and reduced tank volume, maneuverability, and contingency recovery. Increased maneuverability is of critical importance because it enables the client satellite to increase coverage, avoid threats, and increase imagery resolution through orbit shifting.

In this section, we will first focus on the on-orbit assets of the Orbital Express program. The on-orbit assets of the Orbital Express program are categorized in three types:

- Autonomous Space Transfer and Robotic Orbiter (ASTRO), which is the spacecraft performing the servicing.
- Commodities Spacecraft (CSC), which contains the propellant and/ or ORUs[36]. This spacecrafts have more passive roles than the ASTRO spacecrafts, and they typically remain in a fixed orbit.
- The next generation of serviceable client satellites.

The demonstration of a single ASTRO satellite and its performance is scheduled for 2006. For a larger and more complex servicing infrastructure, the operational timeline is envisioned to be in the post-2010 period. Figure 7.1 shows an overview of the operational concept of the Orbital Express program.

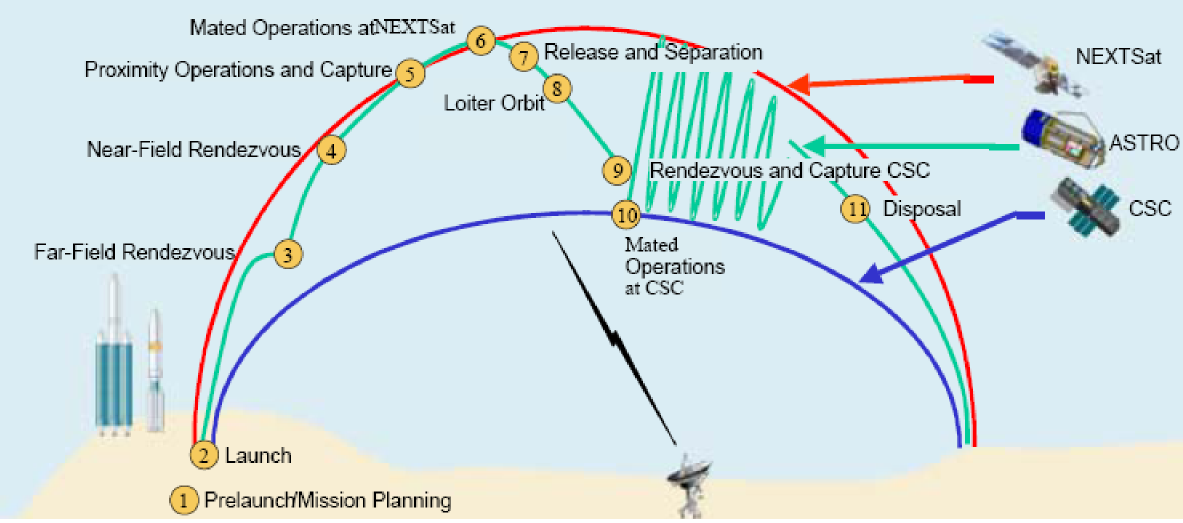


Figure 7.1. An overview of operational concept of the Orbital Express program (source: Potter 2003)

---

[36] ORU: Orbital replacement units, which are replacement components, reconfigured into packages.

The ASTRO spacecraft performs autonomous rendezvous and proximity operations. These spacecrafts include soft capture, standard interfaces, robotics, fluid transfer, and ORU transfer. The ASTRO spacecraft may carry different types of ORUs, and fluid(s) based on different assigned missions and client satellites. The subsystems on-board the ASTRO spacecraft are as follows (Potter 2003):

- Soft capture
- Standard interface: the interface includes capture, fluid transfer, ORU transfer, electrical, software, AGNC sensors and communication
- Robotics, which will be used for changing ORUs
- Fluid transfer system, which will be able to service multiple client configurations and multiple fluids

The schematics of a suggested design of ASTRO can be seen in Figure 7.2. The first of the ASTRO satellites are build by Boeing for a cost of $113 million, with a spacecraft mass of 700kg (Lewis 2004).

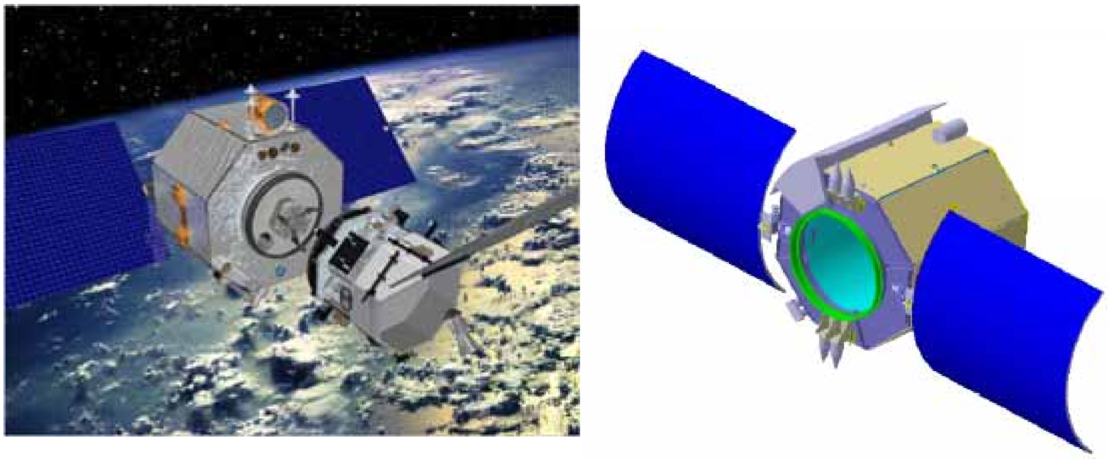


Figure 7.2. ASTRO satellite (Tsien 2003)

On-orbit servicing can create a large value for military, commercial, and civilian space system, while providing flexibility for these systems. Potter (2003) performs a cost benefit analysis for some military space systems, such as refueling ISR-A and ISR-B for life extension and increased maneuverability, and upgrading of SBIRS-low satellites. The possibilities for civil space system include James Webb space telescope, International Space Station and many other opportunities. For commercial space systems, a large pool of client satellites exists. Several satellites are currently located in wrong orbits or contain degrading parts. Many of the next generation satellites will need upgrade in their critical parts in order to avoid the technological obsolescence. With an on-orbit servicing in place, commercial space systems may create a large portion of the total client satellites in the future. The initial phase of the Orbital Express program is granted to Boeing Phantom Works, which collaborates with Ball Aerospace and Technologies Corp., TRW Space and Technology, McDonald Dettwiler Robotics, Charles Stark Draper Laboratory Inc. and Starsys Research Corp to design, manufacture, test, and operate the initial phase of the Orbital Express program.

The measurement of flexibility in the Orbital Express program has great importance, because the funding justification of such a project is dependent to the performance, utilities, and the flexibility provided by this system. In the two case studies studied in this Chapter, we will look at how the 6E flexibility framework can be used to assess the flexibility value of such a system.

7.2 Case study #1: Measuring Flexibility Created by Orbital Express Program for a Set of LEO Client Satellites

In this part of the chapter, we apply the 6E flexibility framework to measure the flexibility provided by a number of different designs of the Orbital Express on-orbit assets located in a LEO sun synchronous orbit. In this section, we look at a set of potential client satellites and a set of architectures for Orbital Express on-orbit assets in LEO to demonstrate the 6E flexibility framework. The system boundary includes the Orbital Express on-orbit assets and its potential clients, which include ASTRO satellites, CSCs, and a limited number of client satellites. The aspect of interest is to measure how flexible the system is with respect to providing a mix of services. Figure 7.3 shows the schematic of the 6E flexibility framework. We will apply and describe each step in details in the following sections.

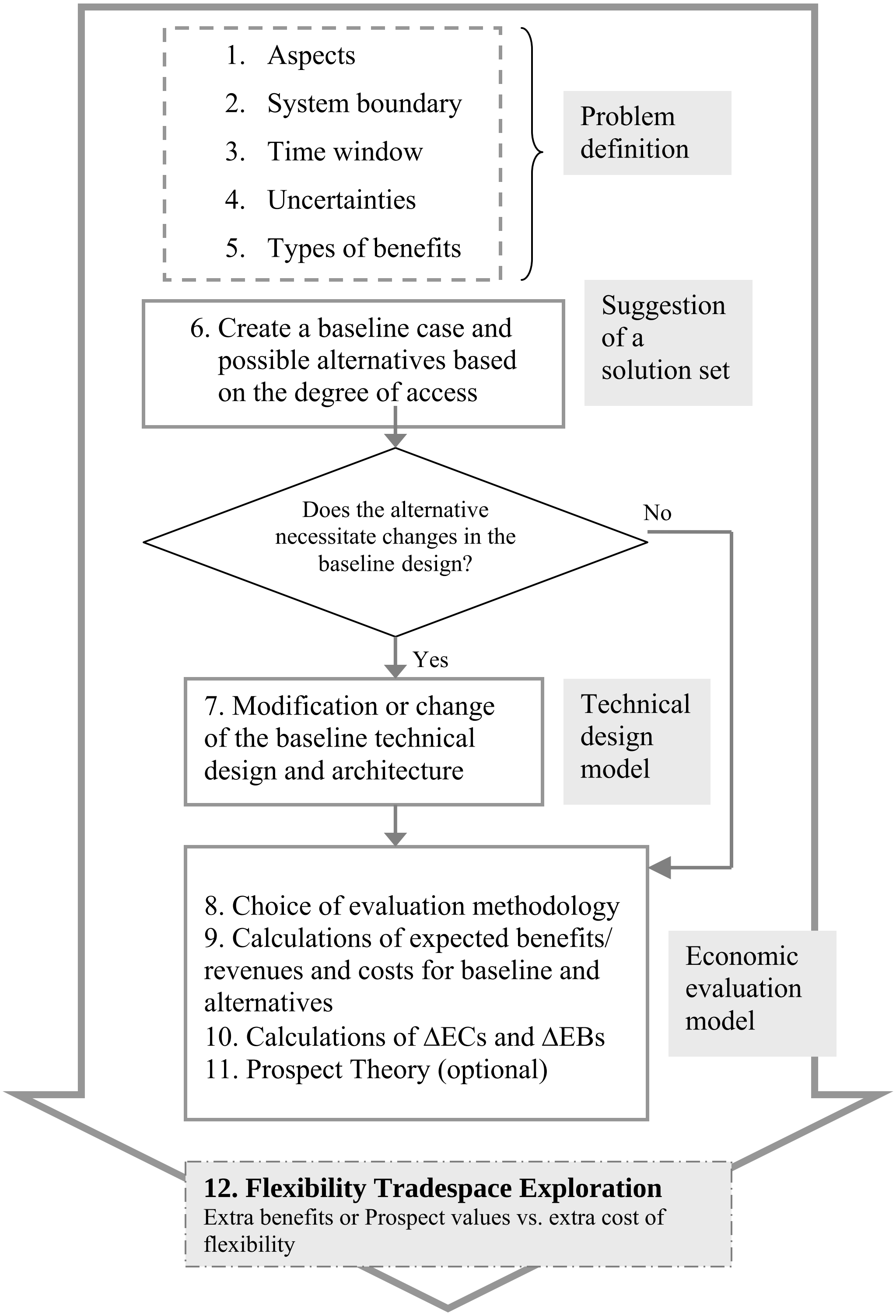


Figure 7.3. 6E flexibility framework

7.2.1 Problem Definition

The first five steps of the framework are extremely important for an accurate definition of the problem. We begin with the definition of aspects of interest, system boundary, and time window, and move to identifying the underlying uncertainties and types of benefits produced. Figure 7.4 shows a high-level diagram for problem definition.

1. Aspect	Mix of services
2. System boundary	Orbital Express on-orbit assets and its client satellites
3. Time window	2010-2020 (10 years)
4. Uncertainties	Technological uncertainties, partial failures, etc.
5. Types of benefits	Detection efficiency

Figure 7.4. Problem definition for Orbital Express case study #1

Aspect of Interest

We choose the aspect of interest as the provision of a mix of services for client satellites. In this case study, we define the following services provided by the Orbital Express system:

- Light refueling, which provides life extension to the client satellites
- Heavy refueling, which provides maneuverability to the client satellite
- Instrument upgrading, which provides a substitution for the existing on-board instrument, and provides the satellite with more capability and efficiency
- Bus electronics upgrading, which provides the client satellite with better and faster processing power

A mix of services here is defined as providing the above sets of services to different sets of client satellite. The client satellites will be described in the following section.

System Boundary

In this case study, the system boundary contains all Orbital Express on-orbit assets and their client satellites. The Orbital Express on-orbit assets consist of a number of ASTROs and CSCs, which create a network system to provide refueling and upgrading to its client satellites. Such a system qualifies to be an Orbital Transportation Network (OTN), which is a suggested mass transportation network in Earth's orbit (Hastings and Nilchiani 2002). In this case study the OTN consists of the following segments:

- Nodes, which are the origin-destination pairs. Usually the origins are the commodities spacecraft (CSCs), and the destinations are the client satellites.
- Links, which specify the actual transportation operations. Usually an ASTRO spacecraft carries the fuel and ORUs from the CSC to the client satellite through such a link or path, determined by orbital mechanics.

Next, we define the client satellites to be serviced. We assume that the initial design of the Orbital Express is geared towards providing life extension to a military space system. Therefore, the major client of the Orbital Express program in this case study is considered to be a constellation of two intelligence and reconnaissance satellite in the sun synchronous orbit (ISR-X). The other client satellites are considered to be civilian satellites in the vicinity of the Orbital Express infrastructure. Figure 7.5 shows the system boundary that includes the servicing infrastructure and the client satellites. The client satellites of the case study #1 are as follows:

- ISR-X constellation
- Landsat X
- Ikonos X

A brief description of each client satellite system is presented here.

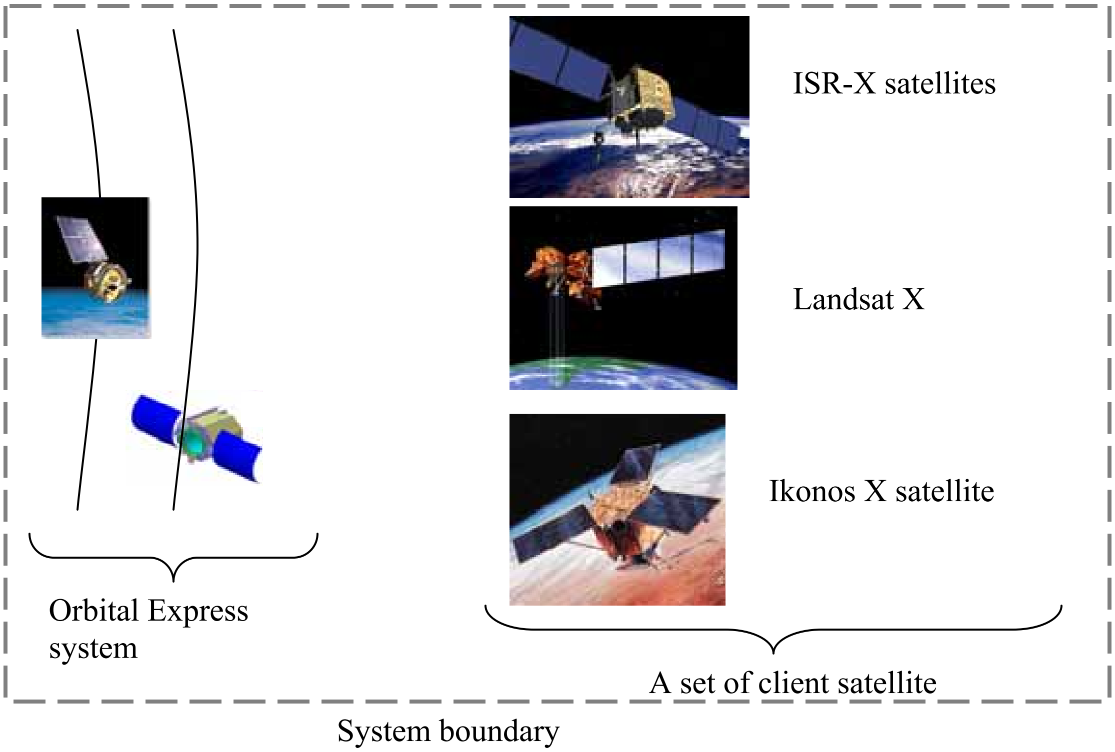


Figure 7.5. A schematic of the Orbital Express system and a set of client satellites

ISR-X Constellation: The ISR-X constellation has a pair of serviceable intelligence, surveillance, and reconnaissance satellites in the low Earth orbit. These satellites are the next generation of the suggested ISR-A and ISR-B satellites that are classified as the military space systems (Potter 2003). We assume the ISR-X constellation consists of satellites with 500kg of mass in a circular 1000km orbit with an inclination of 98.2°. The original lifetime of each satellite is designed to be 3.3 years. The ISR-X constellation is considered to be the primary client satellite for the purpose of life extension through light refueling the satellites. These satellites are also able to perform maneuvers to change their orbit to a considerably lower orbit (e.g., 400 km) when higher resolution images (information) are needed in short-time emergency missions. The limiting factor for performing such maneuvers is the insufficient on-board fuel. Heavy refueling can provide the solution to the life extension and limited maneuverability. The upgrading of the electronics and the instruments (cameras) on board these spacecraft can also improve their performance dramatically.

Landsat X: Landsat X is assumed to be the next generation serviceable satellite substituting Landsat 7, which is designed to perform a long-term Earth observation. Landsat X is assumed to be a joint project between NASA, NOAA, and the US Geological Survey, which continuously creates high-resolution images of the Earth surface. The images are used for environmental monitoring, disaster assessment, regional planning, cartography, range management, oil and mineral exploration, and many other purposes. We assume that the major instrument on Landsat X is Enhanced Thematic Mapper X (ETM^X), which will be the X generation of the current instrument installed on Landsat 7 satellite.

The Landsat X satellite will be located in a circular 700 km orbit with an inclination of 98.2°. Landsat X lifetime is 5 years with an option to extend its life for 6 more years. The satellite weighs 1950 kg and has X-band and S-band transponders on board. The three X-band and one S-band transponders transfer data at rates of 150 Mbps and 2000bps each respectively (Landsat 2005). The Landsat X satellite can benefit from upgrading service provided by the Orbital Express infrastructure on orbit.

Ikonos X: The Ikonos X satellite is a commercial imaging satellite in low earth orbit and assumed to be the next generation of the currently in orbit Ikonos satellite. The Ikonos X satellites are able to take images with resolution less than one meter and they provide high-resolution images of the Earth to its customers worldwide. We assume that the Ikonos X satellite has a mass of 700kg and located in a circular orbit of 680 km and 98.2° inclination. The main payload consists of a digital imaging camera that responds to different assigned tasks by the ground station. The operational design lifetime of this satellite is assumed to be 10 years. The Ikonos X satellite can also benefit from the upgrading services provided by on-orbit servicing.

It should be noted that all theses three space systems (ISR-X, Landsat X and Ikonos X) are in the same orbital plane.

Time Window

The time window of interest in this case study is assumed to be from 2010-2020 (10 years). The beginning of the time window is based on the suggested timeline for deploying the Orbital Express program. The lifetime of the Orbital Express system is greater than 10 years, but we limit our study to a 10-year period time starting from 2010. The replacement for ASTRO and CSCs will assure the continuation of their service for the following decades.

Uncertainty

There are several types of uncertainties that affect our chosen system for case study #1. The major uncertainties are as follows:

- The ORU technological improvement for each client satellite, or the technological readiness of the parts to be upgraded
- The uncertainty related to the success of the Orbital Express in servicing and upgrading with regards to successful rendezvous, fuel and part transfer and exchange with the client satellite
- The uncertainty pertaining to the partial or catastrophic failure of Orbital Express
- The uncertainty relevant to the servicing market, which is introduced in the system through the client satellites. The client satellites may seek on-orbit servicing or they may choose to replace their satellites or abandon them altogether.

The above-mentioned uncertainties are shown in Figure 7.6. The identified uncertainties are divided into provider-side uncertainty, client-side uncertainty, and the uncertainty in the interface of these two, which is relevant to the success of servicing mission.

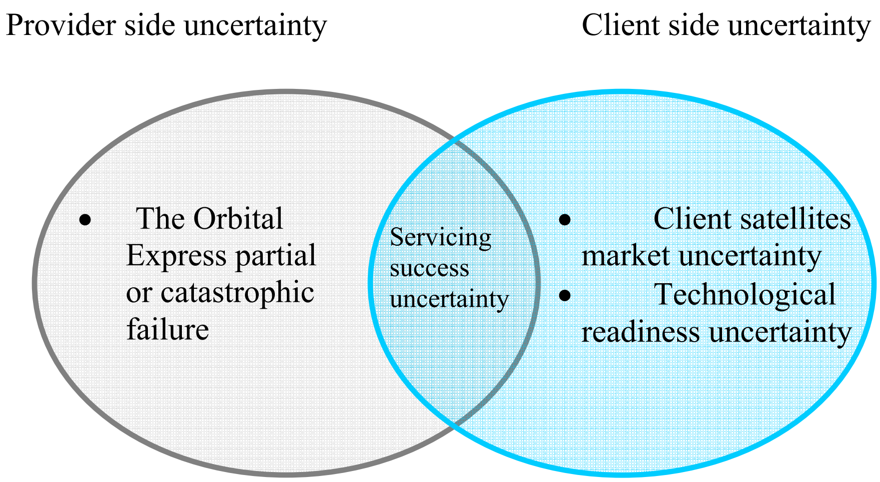


Figure 7.6. A selected set of relevant uncertainties from the provide and client perspective for case study #1

Types of Benefit

In order to measure the benefits created by the Orbital Express program, we assume that the benefits created are equivalent to the resulting increased benefits of the client satellites. In case study #1, the major client of the system is the ISR-X constellation. There are also two other customer satellites, which are considered to be the secondary customer of the Orbital Express system. The three clients of the Orbital Express program do not generate direct monetary benefits; rather they are used for imaging the Earth's surface although with different specifications, goals, and applications.

We define a value function, applicable for all three client satellite systems, since the major products of ISR-X, Landsat X, and Ikonos X are in the form of images. The suggested benefit function should be able to capture the number and quality of the images taken by the satellites. From the literature on satellite imaging instruments and space telescopes, we introduce two different measures for the choice of instrument and its upgrades. The first measure is based on comparing the candidate optical imagery payloads that have similar performance characteristics. The measure is called the *Relative Quality Index (RQI),* which allows for direct quantitative comparison with a reference instrument. Therefore, this measure makes it possible to compare the new instrument to the current on-board instrument. RQI is a measure for high-resolution spatial instruments and uses the signal-to-noise ratio (SNR), the modulation transfer function (MTF), and the ground sample distance (GSD) (SMAD 1999). The relationship is as follows:

$$RQI = \frac{SNR}{SNR_{ref}} \cdot \frac{MTF}{MTF_{ref}} \cdot \frac{GSD_{ref}}{GSD} \tag{7.1}$$

where RQI is the relative quality index, SNR is the signal-to-noise ratio at spatial frequency zero, MTF is the modulation transfer function, GSD is the ground sample distance, and *ref* is for the reference instrument.

The second measure is frequently used for space telescopes such as Hubble Space Telescope (HST). The measure is called *Discovery efficiency*, and it is defined as the field of view multiplied by the throughput of the instrument (HST 2005). The relationship is presented as follows:

$$q = FOV \cdot z \tag{7.2}$$

where q is the discovery or detection efficiency, FOV is the field of view, and z is the throughput of the camera. For this case study, we choose the second measure to build a benefit function.

A suggested benefit function should be able to capture the image quality and the number of taken pictures over a specified period of time. Therefore, the benefit function measures the cumulative number of images over a period of time with consideration of the quality of the images. We define the benefit function as follows:

$$B = \int_{t_0}^{t_n} nq\,dt \tag{7.3}$$

where B is the benefit function generated by an imaging satellite, n is the number of images per unit time, q is the discovery or detection efficiency, and t is the time.

It should be noted that q is also a function of camera's generation, x, and the satellite orbit, r. For a satellite in altitude r, the ground resolution is defined as follows:

$$X = 2.44r\frac{\lambda}{D} \tag{7.4}$$

where X is the ground resolution, λ is the wavelength, and D is the aperture diameter of the optical instrument (SMAD 1999). The relationship shows that the ground resolution improves with maneuver of an imaging satellite to a lower orbit.

The benefit function increases in the following ways:

- Life extension (increasing the time interval of the integral in benefit function)
- Imaging satellite maneuver to lower orbit (improving the ground resolution, and therefore the discovery efficiency)
- Upgrading the imaging instrument (improving the discovery efficiency)
- Upgrading the bus electronics (increase in the number of images taken and processed on board)

The ISR-X constellation produces benefits to the military customer in the form of images for the purpose of intelligence and reconnaissance. For the purpose of reconnaissance, the resolution and quality of the images plays an important role. In addition, the number of images is of great importance. Therefore, the higher the value function, the more benefits is generated by the ISR-X constellation to its customers.

The Ikonos and Land 7 satellites are imaging satellites providing imagery from the surface of the Earth for the purpose of commercial, civilian, and scientific uses. A similar benefit function is defined for measuring the benefits generated by Ikonos X and Landsat X using Equation 7.3. We assume that the two Ikonos X and Landsat X satellites create the same type of benefits to their clients and therefore we can add their benefit together and create a single benefit function for the two satellites. It should be noted that in this benefit function, the improvement in value is a direct function of the number of images taken, processed, and sent back to the ground station rather than the quality of the images. There are regulatory limitations on how refined images can become. Based on Land Remote Sensing Act of 1992 and Presidential Decision Directive (PDD)-23 of March 1994, it is the policy of the United States to encourage the development of commercial satellite imagery systems with a ground sample distance (GSD) resolution of one-meter or less (also known as ultra-high resolution or UHR), but in the post-9/11 era this may again change to the Cold War restriction of 1 meter resolution. Therefore, the major improvement on the next generation of instruments on board of civilian spacecrafts can be made through better and faster processing power.

We can present the benefit function in the following form:

$$B_1 = \int_{t_0}^{t_n} nq\,dt \tag{7.5}$$

$$B_2 = B_{Landsat} + B_{Ikonos} = \int_{t_0}^{t_n} n_L q_L\,dt + \int_{t_0}^{t_n} n_I q_I\,dt \tag{7.6}$$

where B_1 is the benefit generated by the military client satellites and B_2 is the benefit generated by the civilian client satellites. In this case study, we do not add B_1 to B_2 because the importance of the military satellite cases differs from the civilian satellite benefits in the assigned weight to the benefit.

It should be noted that the benefit functions are probabilistic in nature. They depend on the decision nodes and events, and probability distributions exist in the number of images per unit time (n), and the detection efficiency (q). In this case study, a decision tree analysis is used to model the uncertainty of the case. Through modeling the uncertainty in the benefit function, we can calculate the expected benefit associated with each benefit function. The expected benefit functions are ultimately used in calculations of delta benefits in the flexibility tradespace.

7.2.2 Creating a Baseline and Alternatives

In the next step of the framework, we create a baseline and several alternatives to measure the generated flexibility by the Orbital Express program. We assume that the baseline task of the Orbital Express on-orbit asset is light refueling of the ISR-X satellites for the purpose of life extension of the constellation for 10 years. Therefore the baseline case consists of an ASTRO spacecraft that carries 250 kg of fuel for refueling the client satellites in years 2013, 2016, and 2019 respectively. The alternatives are created based on the following criteria:

- Providing different types of services, such as heavy refueling and upgrading
- Providing service to different client satellites besides ISR-X

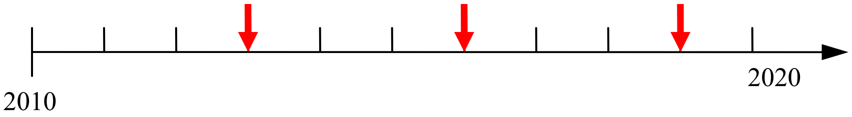
Each alternative is based on a scenario that covers the time window of interest. Each alternative may also incorporate different designs and architectures of the servicing infrastructure. For example, one or several depots may be needed based on the requirements to create each alternative. Table 7.1 shows our assumption for the building elements of the infrastructure on orbit.

Table 7.1. The Orbital Express on orbit elements and their assumed specifications for case study #1

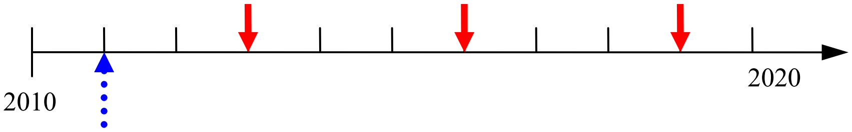
Element	Specifications	comments
ASTRO	• Dry mass = 300kg • Wet mass = 600kg • spacecraft lifetime = 10 years • Orbit = 950 km, 98.2° inclination • Light refueling unit mass = 40kg	The spacecraft usually carries 300 kg of fuel, which is sufficient for 3 times light refueling of the ISR-X satellites. It can also carry larger fuel tanks for the purpose of heavy refueling or carrying different quantities of ORUs
CSC	Two types consist of: • Fuel depots: small (240kg of fuel), medium (480kg of fuel), and large (720kg of fuel) + structure mass of depots • ORU depots :contains the ORUs • Heavy refueling unit mass = 120 kg • ORU mass = 30kg • Orbit = 950 km, 98.2° inclination • spacecraft lifetime = 10 years	Fuel depots are designed in three sizes (240 kg, 480kg, and 720kg). All fuel and ORU depots are located in the same orbit and coplanar with ASTRO and other client satellites. The fuel depots are considered to be launched in alternatives which involve heavy refueling of the client satellites. The ORUs are launched shortly before each upgrading mission

The baseline case needs an ASTRO spacecraft on orbit as the necessary infrastructure. Alternatives 1 to 3 are created based on heavy refueling the ISR-X spacecraft from 1 to 3 times in three years, if emergency missions are required. Therefore, alternatives 1 to 3 need an ASTRO and a fuel depot in 3 different sizes (based on the fuel requirement of each alternative). Alternatives 4 through 6 are created based on upgrading the on-board instruments of the ISR-X spacecrafts for once, twice, and three times in their lifetime. Therefore, these alternatives require one ASTRO and ORU depots launched before each upgrading/servicing missions. Alternatives 7 and 8 are developed on the basis of alternative 6 with the addition of refueling Landsat X in 2015 and Ikonos X in 2014 respectively. The infrastructure in alternatives 7 and 8 consists of one ASTRO and ORU depot with a size depending on the number of carried ORUs. Figure 7.7 shows the schematics of the suggested baseline and alternatives.

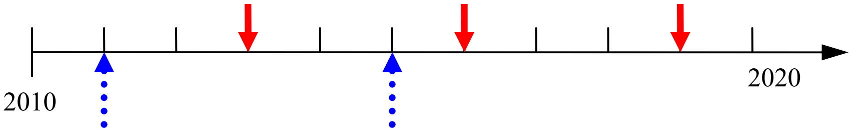
Baseline: ISR-X constellation life extension to 10 years through 3 times of refueling, Landsat X and Ikonos X are not serviced.



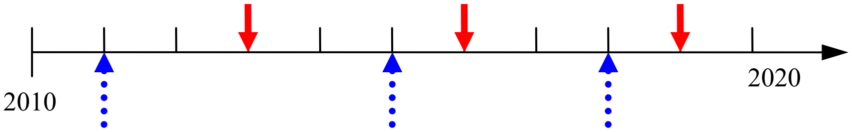
Alternative 1: Baseline case plus refueling ISR-X satellites for one extra *E* mission



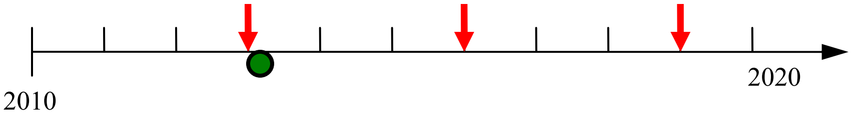
Alternative 2: Baseline case plus refueling ISR-X satellites for two extra *E* missions



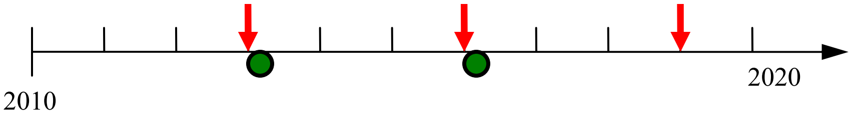
Alternative 3: Baseline case plus refueling ISR-X satellites for three extra *E* missions



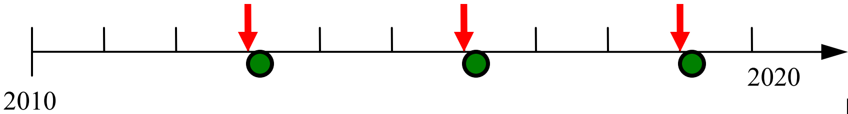
Alternative 4: Baseline case plus one time upgrading of the ISR-X satellites



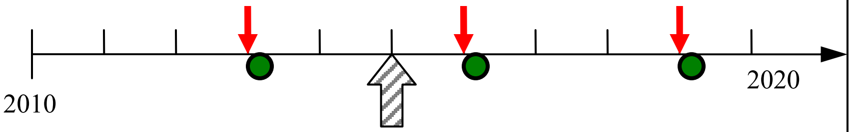
Alternative 5: Baseline case plus two times upgrading of the ISR-X satellites



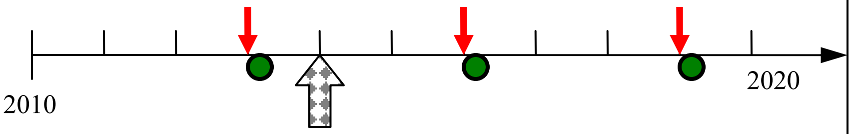
Alternative 6: Baseline case plus three times upgrading of the ISR-X satellites



Alternative 7: Alternative 6 plus Upgrading Landsat X in 2015



Alternative 8: Alternative 6 plus Upgrading Ikonos X in 2014



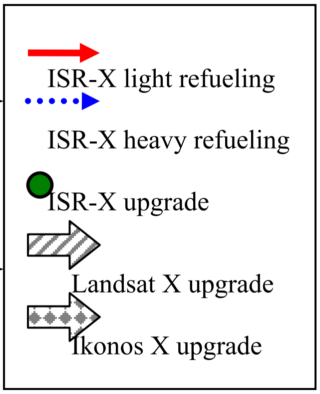


Figure 7.7. Baseline case and a set of alternatives for case study #1

7.2.3 Technical Model

The technical model task is to measure the necessary changes to the on-orbit servicing infrastructure with respect to the original servicing infrastructure. The baseline design of the Orbital Express infrastructure consists of an ASTRO spacecraft that carries 300kg of fuel and is located in the same plane as the client satellites in 950 km orbit. The task of the technical model is to calculate the necessary modification to the original design of the servicing infrastructure to accommodate each of the alternatives.

In order to account for the necessary changes in the infrastructure design, we use orbital mechanics relationships to account for the orbital transfers, fuel consumption, and fuel and ORU depot sizing. The schematic of the technical design model can be seen in Figure 7.8.

Technical design model:

- Orbital mechanics relationships
- Fuel consumption
- Orbital Express on-orbit assets architectures

Figure 7.8. Technical design model for the alternatives

An ASTRO spacecraft is the key element in the Orbital Express architecture in this case study. The baseline case architecture consists of a 600 kg ASTRO which 300kg of its total mass consists of fuel. The on-board ASTRO fuel is used for light refueling of the ISR-X constellation and also performing the orbital transfers. In this case study, we assume that all of the orbital transfers are coplanar and Hohmann transfers, which consumes the least amount of fuel. A brief overview of the basic relationships necessary for orbit transfers and fuel consumption are presented here.

The first step in calculating the ΔV budget begins with calculations of the semimajor axis of the transfer orbit, presented as follows:

$$a_{tx} = \frac{r_A + r_B}{2} \qquad (7.7)$$

where a_{tx} is the semimajor axis of the transfer orbit, r_A and r_B are the initial and final orbits.

Next, we calculate the ΔV necessary for performing a one-way coplanar orbit transfer from the ASTRO orbit to the client satellite orbit. Using a Hohmann transfer, the relationships are as follows:

$$\Delta V_A = 631.3481 \left| \left(\left(\frac{2}{r_A} - \frac{1}{a_{tx}} \right)^{1/2} - \left(\frac{1}{r_A} \right)^{1/2} \right) \right| \tag{7.8}$$

$$\Delta V_B = 631.3481 \left| \left(\left(\frac{1}{r_B} \right)^{1/2} - \left(\frac{2}{r_B} - \frac{1}{a_{tx}} \right)^{1/2} \right) \right| \tag{7.9}$$

$$\Delta V_{one\_way} = \Delta V_A + \Delta V_B \tag{7.10}$$

Next, we choose the propellant type for ASTRO. We assume a specific impulse of 300 for ASTRO's fuel. The specific impulse is defined as follows:

$$I_{sp} = \frac{V_0}{g} \tag{7.11}$$

The ASTRO's required propellant mass for one way trip is calculated using the following relationship:

$$m_p = m_0 \left(1 - e^{-\left(\Delta V_{one\_way} / I_{sp} g \right)} \right) \tag{7.12}$$

where m_0 is the initial vehicle mass, and m_p is the mass of the propellant consumed. It should be noted that m_0 (the initial ASTRO mass) is not constant and is changing frequently. For example, in the baseline case, the initial ASTRO mass is 600kg. After the first refueling trip to ISR-X satellites, the ASTRO satellite has transferred 80kg of its fuel mass to the ISR-X satellites in addition to the fuel consumed for performing the round-trip mission. In some alternatives, different sizes and numbers of fuel and ORU units are attached to the ASTRO for refueling or upgrading the client satellites. Addition of fuel and ORU units increases the total mass of the ASTRO. The technical model should be able to account for the changes in the ASTRO's mass and all required amounts of consumed fuel based on the servicing scenarios.

7.2.4 Economic Evaluation Model

In the economic evaluation model, we choose a decision tree analysis to model the uncertainties of importance. In this case study, we assume that these uncertainties are as follows:

- Servicing success uncertainty
- Technological readiness uncertainty

Figure 7.9 shows high-level schematics of the economic evaluation model.

Economic evaluation module:

- Evaluation methodology: decision analysis
- Benefits: (B_1, B_2)
- Cost: C (ASTRO cost, CSC cost, ORU cost, operation cost, launch cost, servicing failure cost)

Figure 7.9. Economic evaluation model

We model the two uncertainties using decision trees. The first modeled uncertainty is the servicing success uncertainty. Figure 7.10 shows an example of the decision tree for servicing success. Based on each defined alternative, there are several decision nodes in each alternative. Each decision node deals with a decision to service (refuel for life extension, refuel for maneuvering, upgrading). If the servicing mission is performed, we consider three major outcomes for the servicing mission:

- The servicing mission is successful:
    - For a light refueling mission, it increases the number of years of operation for the client satellite.
    - For a heavy refueling mission, it improves the discovery efficiency for the duration of the emergency missions.

    - For an upgrading mission, it improves the number of images and the discovery efficiency of the client satellite.

- The servicing mission is not successful and the client satellite is unharmed.
- The servicing mission is not successful and the client satellite is harmed. In this situation, the client satellite will become dysfunctional.

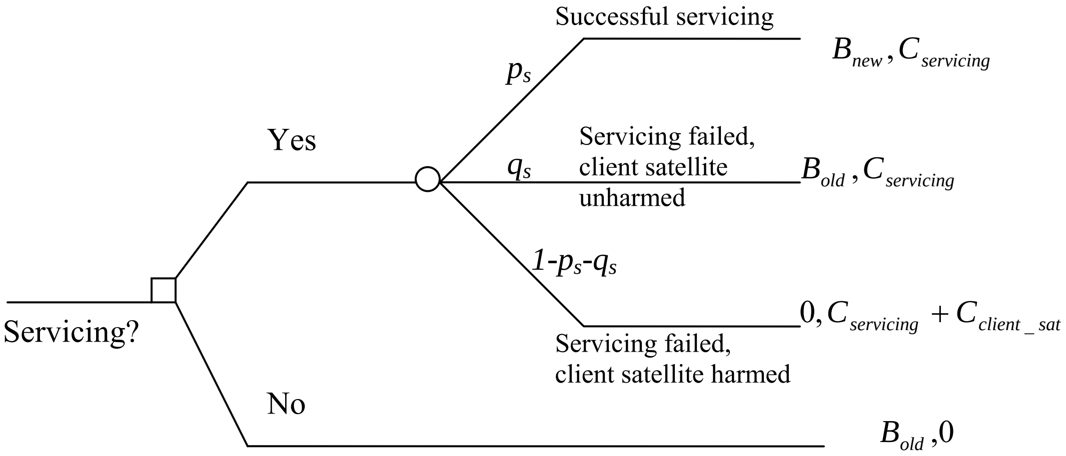


Figure 7.10. Decision tree for servicing success

The second uncertainty of importance is also modeled using a decision tree analysis. This uncertainty is related to the technological readiness of the ORUs and affects the alternatives, which involve an upgrade in client satellite's instrument or bus electronics. If a decision to upgrade is made, a probability distribution function exists for the improvement in outcomes (benefits) of the client satellites.

Benefit Model

The benefit model calculates the expected benefit of the baseline case and each alternative. Examples of calculations of the expected benefit for the baseline case and some alternatives are presented here.

The baseline case assumes three times refueling of the ISR-X satellites for the purpose of life extension. As presented before, the general benefit function for this case study has the following form:

$$B_1 = \int_{t_0}^{t_n} nq\,dt$$

The expected benefit for the baseline case assuming independent probability of success is calculates as follows:

$$EB_{1,baseline} = \int_{t_0}^{t_3} nq\,dt + p_s \int_{t_3}^{t_6} nq\,dt + p_s \int_{t_6}^{t_9} nq\,dt + p_s \int_{t_9}^{t_{10}} nq\,dt \qquad (7.13)$$

where $EB_{1,baseline}$ is the expected benefit of the baseline case, and p_s is the probability of successful servicing mission. If we assume n (number of images per unit time) and q (discovery efficiency) remain constant in client satellite's lifetime, the expected benefit of the baseline case will be as follows:

$$EB_{1,baseline} = nq(t_3 - t_0) + p_s nq(t_6 - t_3) + p_s nq(t_9 - t_6) + p_s nq(t_{10} - t_9) \qquad (7.14)$$

The time step is one year, therefore the expected benefit for the baseline is presented as follows:

$$EB_{1,baseline} = nq(3 + 7p_s) \qquad (7.15)$$

The expected value of the alternative 4 is calculated assuming an additional upgrade of the client satellite's instrument in year 2013. The relationship is presented as follows:

$$EB_{1,Alt4} = nq(t_3 - t_0) + p_s nq_{u_1}(t_6 - t_3) + p_s nq_{u_1}(t_9 - t_6) + p_s nq_{u_1}(t_{10} - t_9) \qquad (7.16)$$

where q_{u_1} is the improved discovery efficiency after the first upgrading mission. q_{u_1} is calculated through considering the probability distribution of the technology readiness of the orbital replacement units. We assume that the improved discovery efficiency has the following relationship:

$$q_{u_1} = \alpha_{u_1} \cdot q \tag{7.17}$$

where α_{u_1} is the technology improvement coefficient . The expected benefit of the alternative 4 is presented as follows:

$$EB_{1,Alt4} = nq\left(3 + 7 p_s \alpha_{u_1}\right) \tag{7.18}$$

The expected value for the other alternatives is calculated in a similar way depending on the scenario of each alternative.

Cost Model

The cost model consists of several parts, which includes the original ASTRO cost, CSC cost (a function of the CSC size), ORU cost, servicing failure cost, operation cost, and the launch cost. The main source of our cost model is Cost Estimating Relationships (CER) from Space Mission Analysis and Design (SMAD 1999) and Boeing information on the Orbital Express program (Potter 2003). A schematic of the cost model can be seen in Figure 7.11.

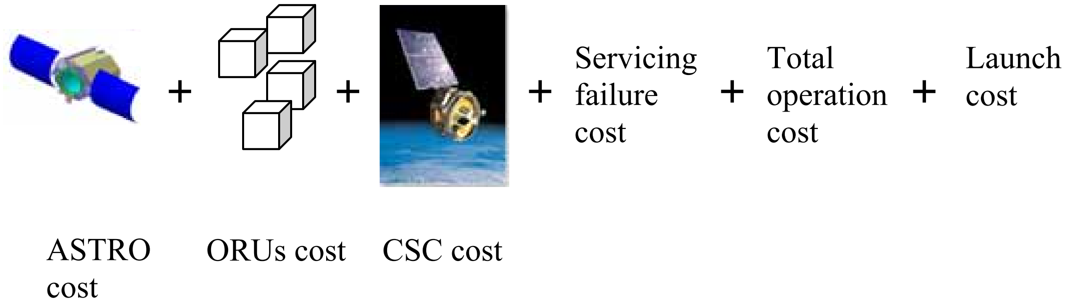


Figure 7.11. A schematic of the Orbital Express cost model for case study #1

In general, we can present the Orbital Express costs for case study #1 as follows:

$$C_{OE} = C_{ASTRO} + C_{CSCs} + C_{ORUs} + C_{launch} + \sum_{i=1}^{10} \frac{C_{i,operation}}{(1+r)^i} + C_{failure} \tag{7.19}$$

where

C_{OE} = Total cost of the Orbital Express for case study #1

C_{ASTRO} = Original cost of ASTRO

C_{CSCs} = Cost of extra CSCs

ΔC_{ORUs} = Cost of the ORUs

C_{launch} = Launch cost

$C_{i,operation}$ = Operation cost in year *i*.

$C_{failure}$ = Cost of the servicing mission failure while harming the client satellite

It should be noted that the cost of failure consists of two parts. The first part represents the cost of unsuccessful servicing mission, while the client satellite is unharmed. The second part of the failure cost is associated with failure of the servicing mission, while the ASTRO damages the client satellite. The second failure cost represents the major cost of the failure. The cost of each alternative is calculated according to each alternative’s scenario.

In the next step, the extra expected benefits and costs are calculated relative to the baseline case. For case study #1, the baseline and alternatives will have the following vector form:

$$Base = \left(EB_1, EB_2, EC_{Base}\right)$$

$$Alt_x = \left(EB_{x1}, EB_{x2}, EC_x\right)$$

The ΔEBC_x vector is calculated to be as follows:

$$\Delta EBC_x = \left(\Delta EB_{x1}, \Delta EB_{x2}, \Delta EC_x\right) \tag{7.20}$$

where ΔEBC_x shows the different types of extra benefits and the associated cost of alternative *x*. This information will be used in the next section to create a flexibility tradespace.

7.2.5 Flexibility Tradespace Exploration and Results

In the last step of the 6E flexibility framework, we create a flexibility tradespace and compare the flexibility of each defined alternative to the baseline case. We make a set of assumptions in order to present the flexibility tradespace results. The assumptions are summarized in Table 7.2.

Table 7.2. The major assumptions for case study #1

Client satellite	Assumptions
ISR-X	Emergency maneuvers: $q_{emergency} = 2.5q$ $t_{emergency} = 1/2$ year Upgrading missions: $q_{u_1} = 3q$ (first upgrading mission) $q_{u_2} = 7q$ (2nd upgrading mission) $q_{u_3} = 15q$ (3rd upgrading mission) Probabilities: $p_s = 0.9$ probability of servicing mission success
Landsat X	$B_{Upgraded\ \ Landsat} = 3B_{Landsat}$
Ikonos X	$B_{Upgraded\ \ Ikonos} = 2.7B_{Ikonos}$ $B_{Ikonos} = 1.8B_{Landsat}$
	Other assumptions: ASTRO cost = \$250 M (ASTRO's cost to orbit) Single ORU mass = 30kg Light refueling mass = 40kg Heavy refueling mass = 120 kg Launch cost = \$120 k/kg

The flexibility tradespace for case study #1 is presented in Figure 7.12 based on the assumptions in Table7.2. The eight different alternatives are shown in this tradespace. The unit of the delta cost axis is in million dollars and the unit of the delta benefit 1 axis is *nq*. As can be seen in this figure, the alternatives associated heavy refueling of the ISR-X satellites are not flexible relative to the alternatives involving the upgrade of the instrument on-board of the client satellites. It should be noted that the tradespace in Figure 7.12 shows only delta expected benefit 1 versus delta cost.

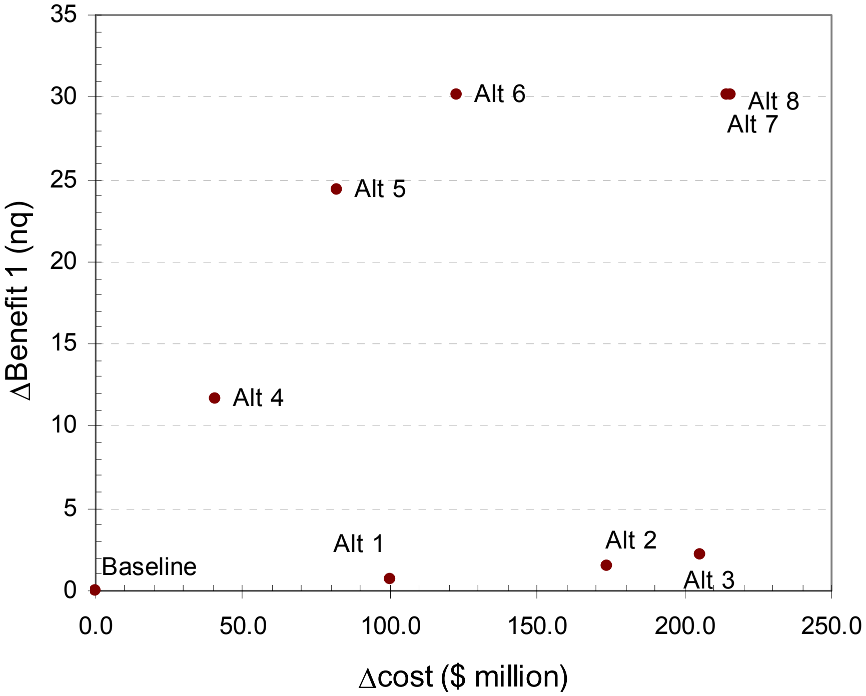


Figure 7.12. Flexibility tradespace for case study #1

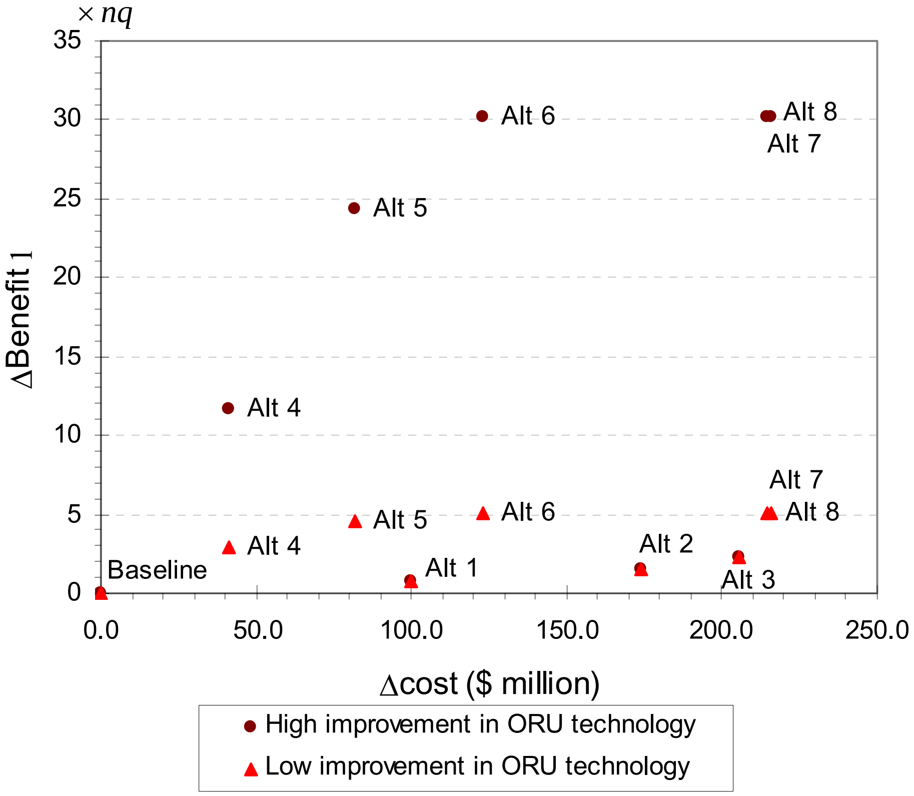


Figure 7.13. Flexibility tradespace

Figure 7.13 shows the flexibility tradespace for the alternatives in two distinct scenarios. The first scenario assumes improvement of 3, 7, and 15 times in the discovery efficiency of the ISR-X instrument in first, second, and third upgrade in 2013, 2016, and 2019 respectively. The second scenario considers a very low in improvement of the discovery efficiency of the instrument. The improvements are considered 1.5, 2, and 2.7 times of the original instrument on-board of the ISR-X satellites. As can be observed from Figure7.13, even with a low improvement in ORU technology, the upgrading alternatives (Alternatives 4, 5, 6, 7, and 8) still show more flexibility in comparison with heavy refueling alternatives (Alternatives 1, 2, and 3). Based on our experience from the Hubble Space Telescope, the improvement in the instrument discovery efficiency (the ORU technology) is more likely to be similar to the first scenario.

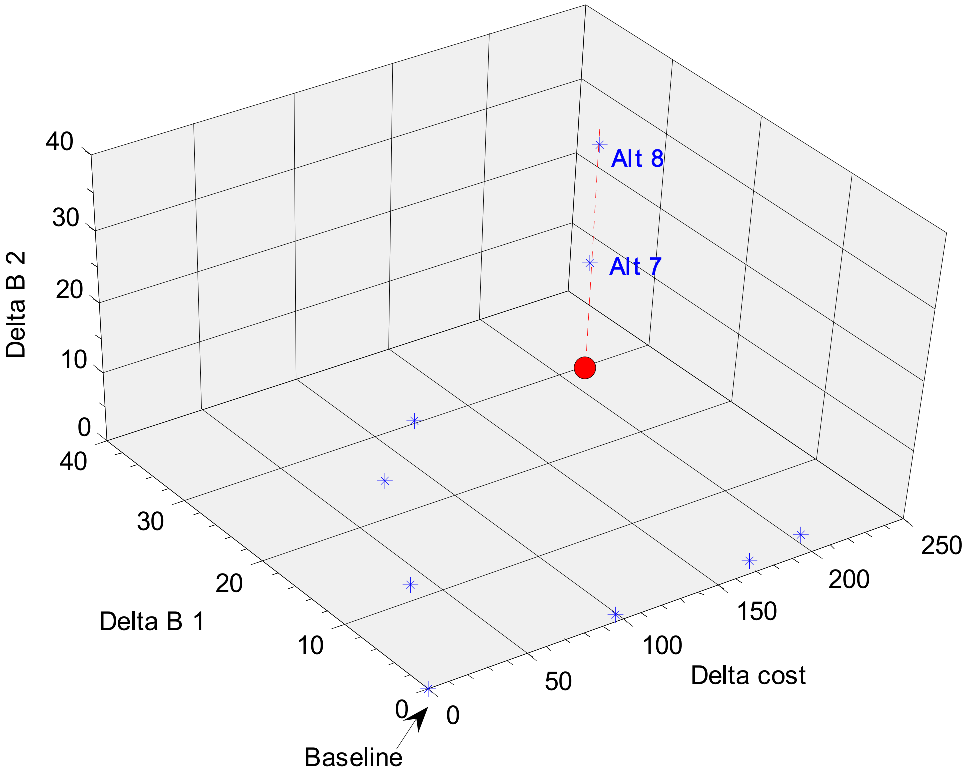


Figure 7.14. Flexibility tradespace for case study #1

Figure 7.14 shows the flexibility tradespace in 3 dimensions. As can be seen in the figure, the alternatives 1 through 6 are located on the delta cost-delta B1 plane. Alternatives 7 and 8 also create benefit for the Landsat X and Ikonos X satellites, which their extra benefit is shown by delta benefit 2.

To summarize, the following points can be highlighted with regards to case study #1:

- On-orbit servicing provides a large amount of flexibility for the client satellite systems.
- The existence of an on-orbit servicing infrastructure provides an opportunity for a set of potential clients in the same orbital plane as the major client of the Orbital Express infrastructure. Change of orbital planes to provide servicing to another client satellite is extremely fuel consuming in most cases and not cost-effective for the servicing infrastructure. For example, if an ASTRO changes its plane from an orbit of 700 km and 98. 2° to service a client satellite located in 950 km and 110°, the required delta V is 1.538 km/s, which is associated with a large fuel consumption on-board the ASTRO.
- In case study #1, we consider a basic refueling for the purpose of life extension as the baseline case. With respect to this baseline, the instrument and bus electronics upgrade provides a large amount of capability and creates a large value of flexibility to the client satellite system. In comparison to the option to upgrade, refueling for performing short-term maneuvers is relatively less beneficial and less flexible.

7.3 Case study #2: Measuring Flexibility Created by Orbital Express Program for a Set of GEO Satellites

In case study #2, we look at some possible Orbital Express servicing structures in geosynchronous orbit and some possible ways through which such a system can create flexibility in its client satellites. We assume a baseline case that considers a basic infrastructure for providing upgrade of critical components to the Milstar satellites. In this case study, we consider the Milstar satellites as the primary client of the Orbital Express system. Assuming a basic servicing infrastructure GEO, we also look at some possible commercial and scientific spacecrafts that can benefit from the Orbital Express infrastructure in GEO. In this case study, we look at the U.S. commercial satellites as the secondary client and we look at some modifications in architecture of the Orbital Express infrastructure which can result in providing services to larger number of commercial satellites. Finally, we look at the possibility of providing services to scientific satellites such as James Webb space telescope, which is located in L2.

We use the 6E flexibility framework in case study #2. Figure 7.3 shows twelve steps of this framework. Each step and their application to case study #2 are presented in the following sections.

7.3.1 Problem Definition

The first steps of the 6E flexibility framework define the problem and clarify the boundaries of the case study. Figure 7.15 shows an schematic of the first five steps of the 6E flexibility framework. We will describe each step of the problem definition here.

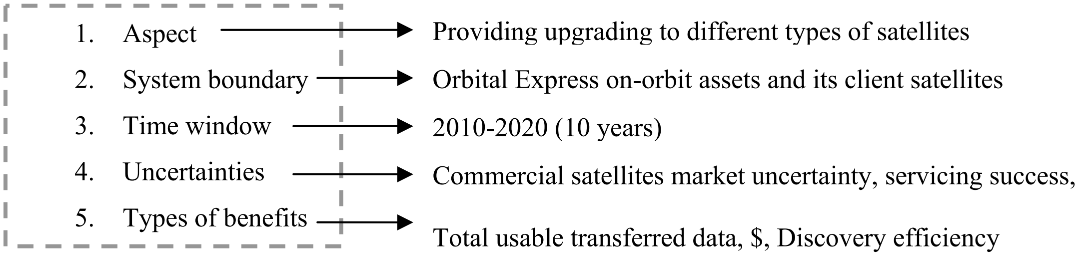


Figure 7.15. Problem definition for Orbital Express case study #2

Aspect of Interest

The aspect of interest in case study #2 is providing upgrading services to the primary client satellite system, Milstar, as well as secondary clients such as commercial and scientific space systems. We are concerned with measuring the amount of flexibility created for the potential client satellites in geosynchronous orbit through existence of an on-orbit servicing infrastructure.

System Boundary

In this case study, the system boundary contains all Orbital Express on-orbit assets in GEO and their client satellites. The possible client satellites are as follows:

- Milstar satellites
- Commercial space systems
- James Webb space telescope

The Orbital Express on-orbit assets include a number of ASTROs and CSCs which were described earlier in this chapter. Figure 7.16 shows the elements inside the system boundary of the case study #2. The ORUs are assumed to be provided by each client satellite company for their specific spacecrafts. A brief description of a selection of the possible client satellites are described here.

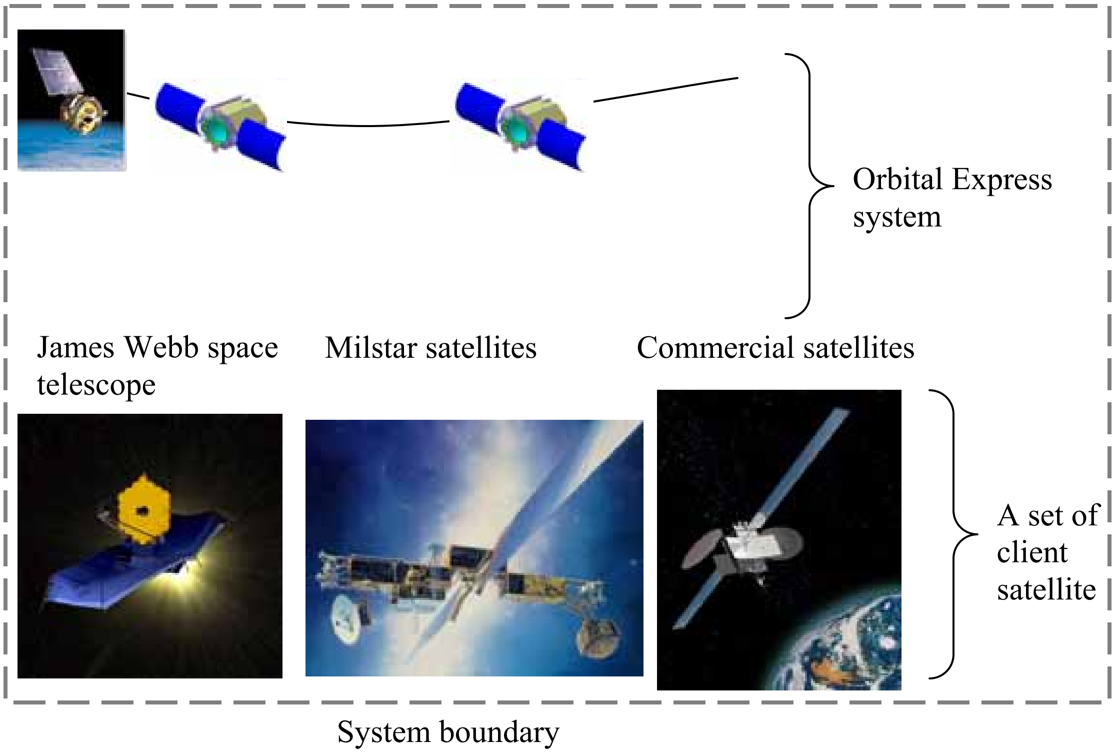


Figure 7.16. A schematic of the Orbital Express system and a set of client satellites for case study #2

Milstar Satellites: Milstar is the most advanced communication satellite system that provides secure, worldwide communication for high priority military uses. The operational Milstar satellites consist of five satellites in geosynchronous orbit. Each satellite can process the communication signal and crosslink with other Milstar satellites, which reduces the ground control switching process dramatically. Each satellite approximately weighs 4530kg and has a 10-year lifetime and costs almost $800 million. Milstar satellites have two major payloads as follows:

- Low data rate communications (voice, data, teletype and facsimile) at 75 bps to 2,400) bps

- Medium data rate communications (voice, data, teletype, facsimile) at 4.8 kbps to 1.544 bps (Satellites 4 through 6 only)

All Milstar satellites include the first payload. The second payload is installed on Milstar 4, 5 and 6 (Milstar 2004).

In this case study, we assume that a basic Orbital Express infrastructure will provide a payload upgrade to the next generation of the Milstar satellites or Milstar AEHF (Advanced Extreme High Frequency Satellite). The number of Milstar AEHF satellites to be serviced is assumed to be 3.

Commercial Satellites: the geosynchronous orbit is the location for a large number of commercial satellites providing several different types of services such as voice, data, and video. These satellites are typically massive, expensive, and they have a lifetime more than 10 years. These satellites are very suitable candidates for payload or part upgrade because they can always improve their performance through usage of latest technologies and avoid technological obsolescence. We consider the U.S. commercial satellites in geosynchronous orbit (such as DirecTV satellites, XM satellites, etc) as a pool of possible secondary clients for the Orbital Express program in GEO. Figure 7.17 shows a forecast of the number of future commercial geosynchronous satellites by Futron (Futron 2004). As can be seen in the figure, the projected number of new satellites ranges from 8 to 14.7 satellites per year. We assumed that the satellites launched after 2006 have a modular structure and they can be upgraded if on-orbit servicing is available.

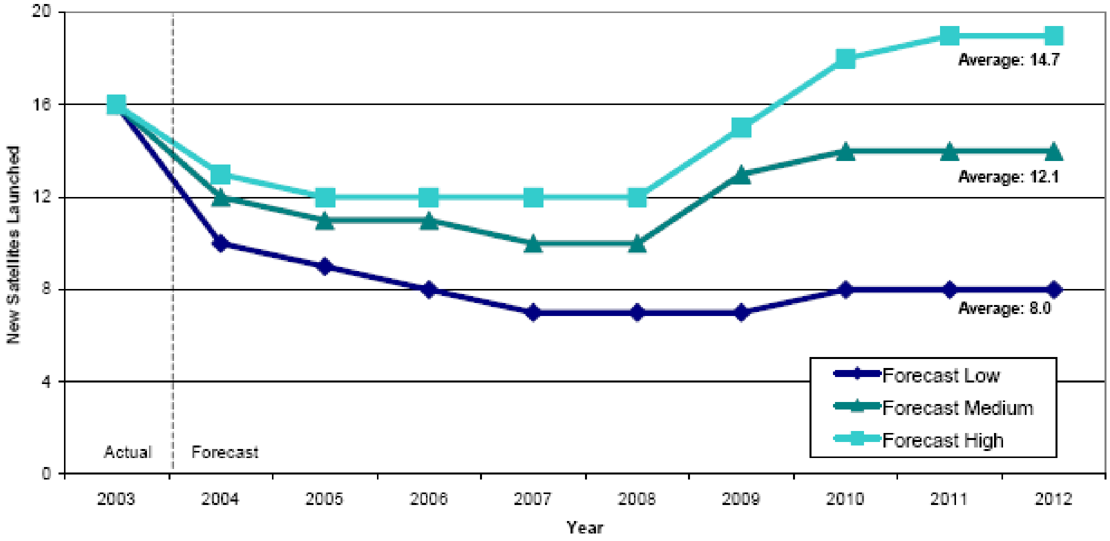


Figure 7.17. A forecast of the number of future launches of commercial satellites to geosynchronous orbit by Futron corp. (Futron 2004)

James Webb Space Telescope (JWST): This telescope is an orbiting infrared observatory proposed to replace the Hubble Space Telescope in 2011. The James Webb space telescope science objectives are determining the shape of the Universe, explaining the evolution of the galaxy, the birth and formation of the stars, formation and interaction of the planetary systems, chemical/elemental composition analysis, and studying the nature of dark matter. The telescope weighs approximately 6200 kg, which includes the observatory and on-orbit consumables. The design lifetime of the satellite is 5 to 10 years.

The JWST will be located at L2 point, which is 1.5 million kilometer from the Earth. Figure 7.18 shows a suggested trajectory and the plan for insertion the James Webb space telescope to L2 orbit.

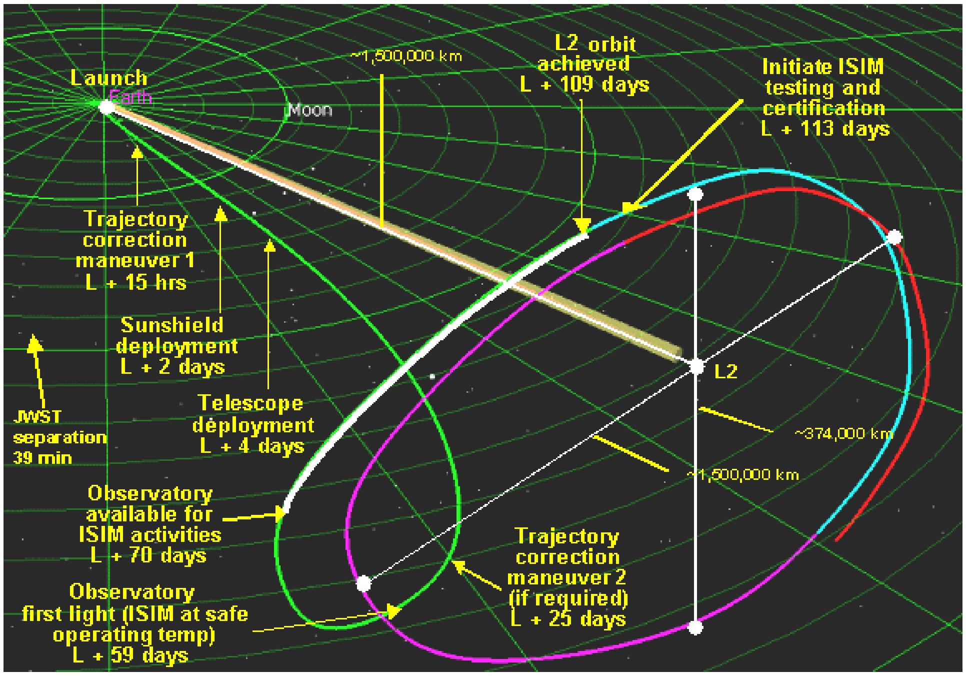


Figure. 7.18.

The JWST major instruments are Near Infrared Camera (NIRCam), Near Infrared Spectrograph (NIRSpec), Mid Infrared Instrument (MIRI), and Fine Guidance Sensors (FGS). The cost of JWST is estimated to be $4.5 billion, which makes the servicing very attractive for this space telescope.

Time Window

The selected time window for case study #2 is considered to be from 2010 to 2020. The beginning of time window is based on the suggested timeline for deploying the Orbital Express program by DARPA.

Uncertainty

There are several types of uncertainties that affect the benefits and costs of the chosen system. The major uncertainties are summarized as follows:

- The uncertainty relevant to servicing market for commercial client satellites.
- The ORU technological improvement for military, commercial, and scientific client satellite, or the technological readiness of the parts to be upgraded. In this case study, we assume that the customer satellites in each year are 5+ years old, which increases the existence of better ORU technology.

- The uncertainty related to the Orbital Express success in servicing and upgrading.
- The risk of partial or catastrophic failure

The two major uncertainties modeled in this case study are the commercial client satellites market uncertainty, and servicing success uncertainty. It should be noted that the market uncertainty for commercial satellites is an external uncertainty while the servicing success is an internal uncertainty of the system. Both of the uncertainties are modeled and described in the following section.

Types of Benefit

An Orbital Express infrastructure can create different types of benefits. The types of benefits depend on the client satellites to be serviced. In case study #2, three major client satellites exist. The primary client satellite system is considered to be the next generation of the Milstar satellites. Upgrading the payload (digital transponders) enables the next generation of the Milstar satellites to be able operate with a higher data rate and process the on-board tasks faster. Therefore, we define a benefit function that measures the amount of transferred data over the time window of study of the Milstar satellite systems. The benefit function is thus defined as follows:

$$B_{Milstar} = \int_{t_0}^{t_n} \nu(x)dt \tag{7.21}$$

where $B_{Milstar}$ is the benefits generated by Milstar system, $\nu(x)$ is the data rate which is a function of payload generation *x*.

The second type of benefit initiates from the commercial client satellites. The upgrade of the bus electronics, transponders, etc. enables the client satellite to increase its revenue and stay competitive in the relevant business. We assume that because the commercial satellites are not the primary clients, the only reason to service these satellites is in the case if they can create additional revenue for the Orbital Express program. This additional revenue is in the form of the amount of money charged per servicing per satellite, which depends on the type of upgrading (e.g., number of upgraded transponders, or bus electronics). Therefore, in this case study, we consider the second type of benefit as the monetary form, and for simplification, we consider an average price of servicing, *S* and we assume that the commercial satellites have the opportunity to be serviced once in the their half life. The benefit function is as follows:

$$B_{commercial} = \alpha n_{com\_sats} S \tag{7.22}$$

where $B_{commercial}$ is the benefit created by servicing a number of commercial satellites, α is the percentage of the commercial satellites which are willing to be serviced, n_{com_sats} is the number of commercial satellites which potentially can be serviced, and S is the servicing price charged after a successful servicing mission of the client satellite.

It should be noted that α, or the percentage of the commercial satellites willing to be serviced, plays an important role in the benefits gained through the commercial satellites. α is a function of the market condition for the commercial satellites' sector. For example if the market condition for the services provided by commercial satellites in 2015 improves form its current state, the percentage of commercial satellites willing to perform the upgrade are larger than if the market will stay the same. The details of the modeling of α and the number of potential client satellites are discussed in the economic evaluation model.

The third type of benefit is associated with the possible upgrade of the James Webb space telescope. A possible instrument or bus electronics upgrade can improve the discovery efficiency of the telescope. We use the following relationship for measuring the benefit gained through the upgrade of JWST:

$$B_{JWST} = \int_{t_0}^{t_n} nq\,dt \tag{7.23}$$

$$q = FOV \cdot z$$

where *B* is the benefit function generated by an imaging satellite, *n* is the number of images per unit time, *q* is the discovery efficiency, FOV is the field of view, z is the throughput of the camera, and *t* is the time.

In this case study, three different types of benefits are involved based on different alternatives. The baseline involves the benefit related to servicing the Milstar satellites, or $B_{Milstar}$. If an alternative also involves servicing a number of commercial satellites, $B_{commercial}$ becomes important. If an alternative involves servicing the JWST, B_{JWST} becomes another type of produced benefit of the system.

7.3.2 Creating a Baseline and Alternatives

In the next step, we define a baseline and a set of alternatives. The baseline is considered to be servicing the three Milstar satellites as the major clients of the Orbital Express in geosynchronous orbit. The alternatives are constructed based on different possible architectures of the Orbital Express that can provide servicing to the commercial satellites and JWST.

The baseline case is assumed to be servicing the three Milstar satellites in the first, second, and the third year from the beginning of the operation of the Orbital Express. The necessary architecture is assumed to be a single ASTRO and three 80kg ORUs which are being launched at the beginning of the servicing mission. Figure 7.19 shows the timeline of servicing and deployment of such infrastructure for the purpose of servicing the three Milstar satellites.

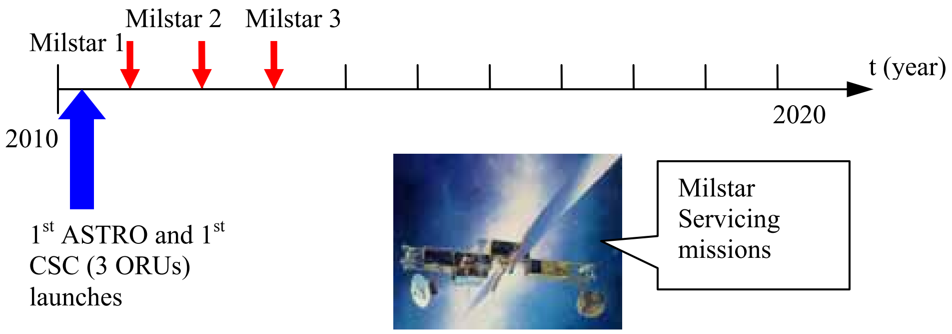


Figure 7.19. A schematic of the baseline case for case study #2

In defining the alternatives, we are concerned with the issue of extra value generated by servicing a set of commercial geosynchronous satellites. Therefore, we look at different architectures based on the number of ASTRO and CSC spacecraft. A larger Orbital

Express architecture can service a larger number of commercial satellites, while smaller architectures may be unable to match the market for satellite servicing.

The major variables in creating the different architectures of the Orbital Express are the number of ASTROs and CSCs as well as the timeline of their deployment. Here, we consider the number of ASTROs ranging from 1 to 3 and the number of CSCs form 1 to 5. We consider a limited effective servicing lifetime for the ASTRO spacecrafts, which is limited by the number of servicing missions performed. Each ASTRO is assumed to be able to perform 25 servicing mission and after accomplishing the 25 missions, the ASTRO is used for less delicate tasks such as tugging, orbital debris removal, and disposal of the old geosynchronous satellites. The replacement for each ASTRO is assumed to be launched a couple of months prior to the retirement of the old ASTRO satellite. The CSC spacecrafts carry the ORUs of the missions for two subsequent years. The first CSC is launched concurrently with the first ASTRO spacecraft in 2010. Based on the different alternatives, different numbers of CSCs are launched with a 2 year intervals. Therefore, we have 15 distinct alternatives for servicing the commercial spacecrafts based on different architectures of ASTROs and CSCs. Table 7.3 shows the specifications of the ASTROs and CSCs for an Orbital Express infrastructure.

Table 7.3. The Orbital Express on orbit elements and their assumed specifications for case study #2

Element	Specifications	comments
ASTRO	• Dry mass = 300kg • Wet mass = 600kg • spacecraft lifetime = 10 years • Orbit = geosynchronous orbit • Total # of servicing mission/ASTRO = 25 (variable)	The spacecraft effective lifetime for the purpose of refueling is assumed to be 25 missions. The ASTROs are retired for the purpose of servicing, but they can still be used for tugging or less delicate missions.
CSC	• CSC :contains the ORUs • ORU average mass = 50kg • Orbit = geosynchronous orbit • ORU launch frequency = 2 years	The CSC spacecraft is a simple structure that contains the ORUs for the next missions. Each CSC carries the ORUs associated with next two year servicing mission.

The last alternative looks at the possibility of servicing the JWST in 2015, four years after the spacecraft is launched to L2 orbit. We assumed that a single ASTRO is tailored for the purpose of servicing the JWST, and the ASTRO will be disposed after the servicing mission. For servicing the JWST, an ASTRO needs to carry a large amount of fuel (almost 70% of the total spacecraft mass for one-way trip to L2), therefore we assume to dispose the ASTRO after the JWST servicing is accomplished. Figure 7.20 shows the JWST servicing alternative (alternative 16).

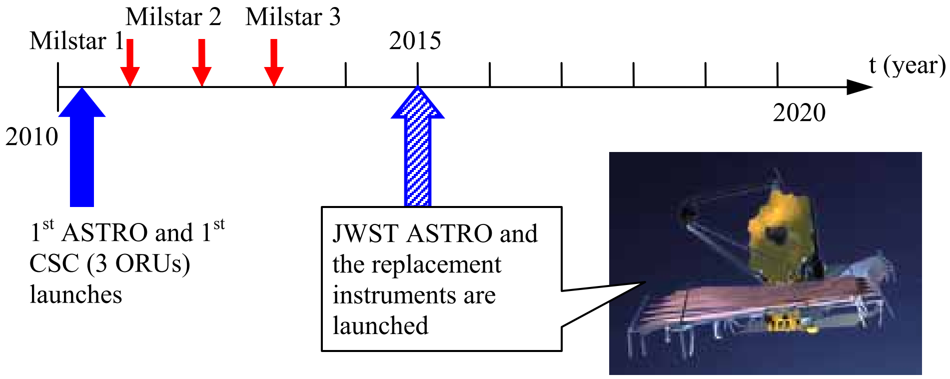


Figure 7.20. A schematic of the JWST servicing alternative

7.3.3 Technical Model

In the technical design model, the orbital transfers, rendezvous, and the fuel consumption of the ASTRO spacecrafts for performing each of the servicing missions are calculated. The reader is referred to the orbital mechanics relationships in section 7.2.3 for calculations of the total amount of fuel required for the servicing missions.

7.3.4 Economic Evaluation Model

In the economic evaluation models, a combination of the binomial lattice and decision tree analysis are used to model the two uncertainties of importance. In this case study, we assume that these uncertainties are as follows:

- Servicing success uncertainty
- Commercial satellite market uncertainty

The servicing success uncertainty is modeled using a decision tree analysis, which is presented in section 7.2.4 of this chapter. The commercial satellite market uncertainty is modeled through a binomial tree, which will be described in this section. Figure 7.21 shows high-level schematics of the economic evaluation model.

Economic evaluation model:

- Evaluation methodology: binomial lattice analysis, decision tree analysis
- Benefits: Total usable transferred data, $, Discovery efficiency
- Cost: C (ASTROs cost, CSCs cost, infrastructure modification cost, operation cost, launch cost, servicing failure cost)

Figure 7.21. Economic evaluation model for case study #2

In case of servicing a number of commercial geosynchronous satellites, we need to model the uncertainty relevant to the commercial satellite market. We use a binomial lattice analysis to model the commercial satellite market uncertainty. Figure 7.22 shows the schematics of a binomial lattice analysis. The tree is constructed using the following relationships:

$$\Delta Y = \sqrt{\sigma^2 \delta t + \left(\alpha - \frac{\sigma^2}{2} \right)^2 \delta t^2} \tag{7.24}$$

$$p = \frac{1}{2}\left(1 + \frac{\left(\alpha - \frac{\sigma^2}{2} \right)\delta t}{\Delta Y} \right) \tag{7.25}$$

where α is the expected drift, σ is the volatility, and δt is the time step of the simulation. The reader is referred to Chapter 6 for more detailed information on the binomial lattice analysis.

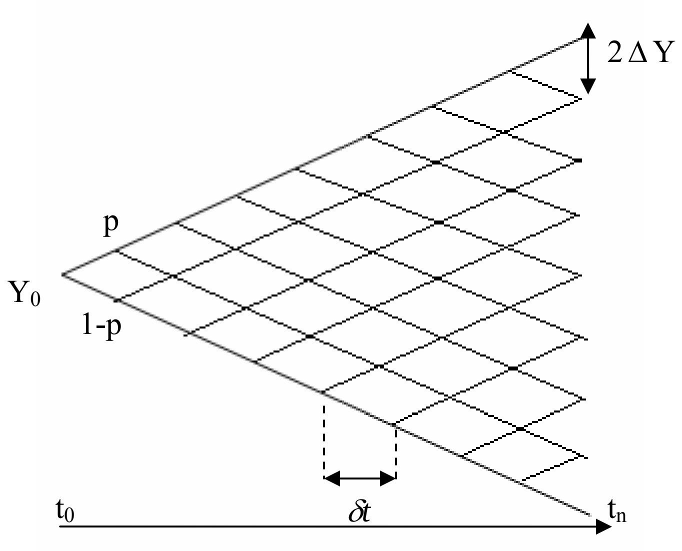


Figure 7.22. A schematic of a binomial lattice

In this case study, the state of the commercial satellites and the market for their services in each stage and state of the tree is normalized with respect to the initial state of the market in 2005, or Y_0. Therefore, Y_0 is 1 in 2005 and the binomial tree models the state of the market from 2005 to 2020. The time window of interest for case study #2 is from 2010 to 2020, therefore a part of binomial tree that includes this selected time window is being used. We assumed that the normalized state of the market in 2005 is 1, the standard deviation $\sigma = 20\%$, the market drift $\alpha = 6\%$, and the time step $\delta t = 1$ year. Figure 7.23 shows the probability distribution of the state of the market in 2010, 2015, and 2020 respectively. The vertical line at 1 shows the normalized state of the market at 2005.

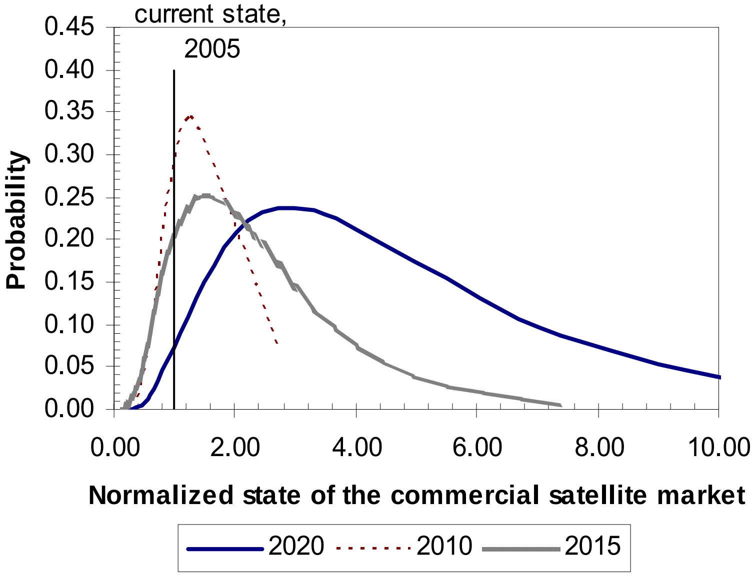


Figure 7.23. Probability distribution function of the state of the commercial market in 2010, 2015, and 2020

After modeling the market and servicing success uncertainty, the next steps are calculating the expected benefits and the expected costs for the baseline and alternatives using the uncertainty models. These calculations are presented in the following sections of this chapter.

Benefit Model

The benefits of case study #2 are in three different forms as follows:

$$B_{Milstar} = \int_{t_0}^{t_n} \nu(x)dt \tag{7.26}$$

$$B_{commercial_{i,j}} = \alpha_{i,j} n_{com\_sats} S \tag{7.27}$$

$$B_{JWST} = \int_{t_0}^{t_n} nqdt \tag{7.28}$$

The expected benefits of the baselines and the alternatives are calculated here.

The baseline case involves servicing of the three Milstar satellites in 2011, 2012 and 2013. Assuming that *p* represents the probability of a successful servicing, the expected benefit of the baseline case is as follows:

$$EB_{Milstar} = EB_{Milstar1} + EB_{Milstar2} + EB_{Milstar3}$$

$$EB_{Milstar} = \int_{2010}^{2011} v_1 dt + p \int_{2011}^{2020} v_2 dt + \int_{2010}^{2012} v_1 dt + p \int_{2012}^{2020} v_2 dt + \int_{2010}^{2013} v_1 dt + p \int_{2013}^{2020} v_2 dt \qquad (7.29)$$

where v_1 is the data rate of the old instruments on-board of the Milstar satellites and v_2 is the data rate after upgrading the Milstar spacecraft. Assuming the two data rates are constant, we have:

$$EB_{Milstar} = v_1 + 9pv_2 + 2v_1 + 8pv_2 + 3v_1 + 7pv_2$$

$$EB_{Milstar} = EB_{baseline} = 6v_1 + 24pv_2 \qquad (7.30)$$

The benefits of the baseline case can be presented in a vector form as follows:

$$EB_{baseline} = (EB_{Milstar}, 0, 0) \qquad (7.31)$$

The vector shows that there is no benefit generated through servicing the commercial satellites and JWST in the baseline case.

In the next step, the expected benefits of the alternatives are calculated. The alternatives 1 through 15 are related to providing services to a number of commercial U.S. satellites in geosynchronous orbit. Therefore $EB_{commercial}$ should be calculated for these satellites. Here, the commercial market uncertainty plays an important role. We assume that we have a pool of potential commercial client satellites in geosynchronous orbit with an average forecast of 15 client satellites per year. If the commercial satellite market grows with respect to its current state (in 2005), the higher percentage of these potential client satellites will be willing to service their satellites, or become the actual clients. We assumed that of the state of the market stays the same as today (normalized value of 1), 30% of the potential client satellites become the actual clients. The percentage of actual clients increases with the higher states of the market until it reaches a cap of 75% for the actual client satellites. The actual number of the client satellites at each stage adds up to the total number of actual client satellites.

$$B_{commercial_{i,j}} = \alpha_{i,j}\left(p_i(\alpha,\sigma), r, \delta t\right) n_{com\_sats} R \tag{7.32}$$

where $B_{commercial_{i,j}}$ is the benefit gained from the commercial satellite market at stage *I* and state *j*, $\alpha_{i,j}$ is the percentage of the potential client satellites willing to be serviced, $p_i(\alpha,\sigma)$ is the probability distribution for each period as a function of drift and volatility, r is the discount rate, δt the time steps, n_{com_sats} is the number of potential client satellites per time step (one year), and *R* is the average price charged per servicing mission.

After calculating the benefits gained at each stage (10 stages from 2010 to 2020) the capability of the Orbital Express architecture is combined with the actual client satellite information, because an architecture may be inadequate to service the actual number of satellites. The alternatives 1 through 15 look at the different servicing structures where the number of ASTROs range from 1 to 3 and the number of CSCs range from 1 to 5. In order to calculate the total benefits gained by servicing the above-mentioned commercial satellites at each stage, we start from the last period in the tree and use a backward iterative process and dynamic programming techniques to calculate the total revenue or benefit generated by servicing a number of commercial satellites. The expected benefits of the alternatives 1 through15 is presented as follows:

$$EB_{Alt\,1-15} = \left(EB_{Milstar}, EB_{commercial}, 0\right) \tag{7.33}$$

The alternative 16 is related to servicing the JWST in 2015. The expected benefit function for the JWST is as follows:

$$EB_{JWST} = \int_{2011}^{2015} n_1 q_1 dt + p\int_{2015}^{2020} n_2 q_2 dt \tag{7.34}$$

where n_1 is the number of images per unit time before upgrade, n_2 is the number of images per unit time after the upgrade is performed, q_1 is the discovery efficiency before upgrade and q_2 is the discovery efficiency after the upgrade is performed. The expected benefit and benefit vector of the alternative 16 is presented as follows:

$$
\begin{aligned}
EB_{JWST} &= 4n_1q_1 + 5pn_2q_2 \\
EB_{Alt16} &= \left(EB_{Milstar}, 0, EB_{JWST}\right) \qquad (7.35)
\end{aligned}
$$

Cost Model

The cost model consists of several parts, which includes the original ASTRO cost, CSC cost (a function of the CSC size), ORU cost, servicing failure cost, operation cost, and the launch cost. The main source of our cost model is Cost Estimating Relationships (CER) from Space Mission Analysis and Design (SMAD 1999) and Boeing information on the Orbital Express program (Potter 2003). A schematic of the cost model can be seen in Figure 7.24.

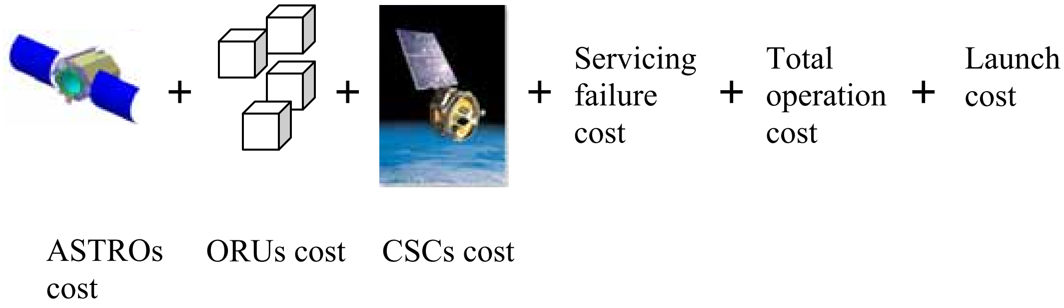


Figure 7.24. A schematic of the Orbital Express cost model for case study #2

In general, we can present the Orbital Express costs for case study #2 as follows:

$$C_{OE} = C_{ASTRO} \times N^{B}_{ASTRO} + C_{CSCs} \times N^{B}_{CSC} + C_{ORUs} + C_{launch} + \sum_{i=1}^{10} \frac{C_{i,operation}}{(1+r)^i} + C_{failure} \qquad (7.36)$$

where $B = 1 - \dfrac{\ln(100\%/S)}{\ln(2)}$

C_{OE} = Total cost of the Orbital Express for case study #1

C_{ASTRO} = Original cost of ASTROs

C_{CSCs} = Cost of extra CSCs

N_{ASTRO} = Number of ASTROs

N_{CSC} = Number of CSCs

S = Learning curve in percentage

ΔC_{ORUs} = Cost of the ORUs

C_{launch} = Launch cost

$C_{i,operation}$ = Operation cost in year *i*.

$C_{failure}$ = Cost of the servicing mission failure while harming the client satellite

7.3.5 Flexibility Tradespace Exploration and Results

In the last step of the 6E flexibility framework, we create a flexibility tradespace and compare the flexibility of each defined alternative to the baseline case. We make a set of assumptions in order to present the flexibility tradespace results. The assumptions are summarized in Table 7.4.

Table 7.4. Major assumptions for case study #2

Client satellite	Assumptions
Milstar	$v_2 = 2.3v_1$ $p_s = 0.9$ probability of servicing mission success
Commercial geosynchronous satellites	$\sigma = 20\%$ $\alpha = 6\%$ $\delta t = 1$ R = \$30 million (changing)
JWST	$n_2 q_2 = 3 n_1 q_1$
	Other assumptions: ASTRO cost = \$250 M (ASTRO's cost to orbit) Average single ORU mass = 50kg Launch cost = \$120 k/kg $S = 95\%$

Based on the assumptions of Table 7.5, the benefits associated with servicing the Milstar satellites will be as follows:

$$EB_{Milstar} = EB_{baseline} = 6v_1 + 24pv_2 = 49.68v_1$$

which shows a significant increase from the case of not upgrading the Milstar satellites ($30v_1$). The expected benefit of the Milstar satellite is considered the baseline case.

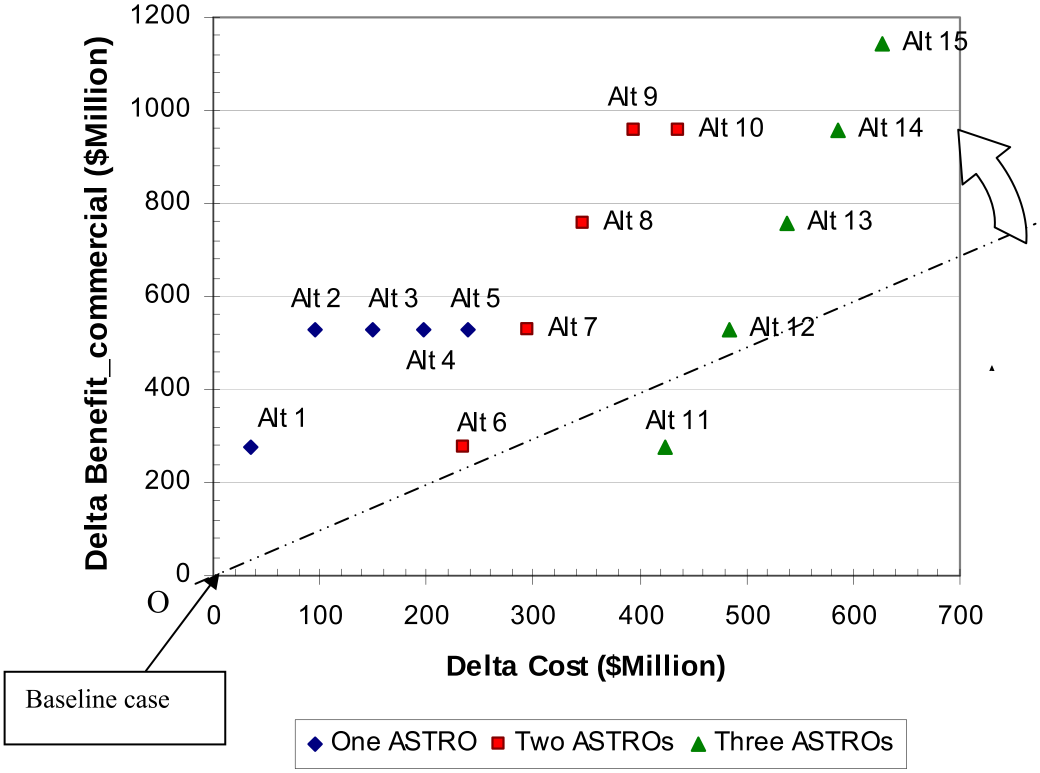


Figure 7.25. Flexibility tradespace of delta $B_{commercial}$ versus delta cost for case study #2

Figure 7.25 shows the flexibility tradespace for alternatives 1 through 15. These alternatives are relevant to servicing a number of commercial satellites. The entire 15 alternatives also include servicing the Milstar satellites and have no change in the benefit associated with servicing the Milstar satellites. Therefore in calculating the delta expected benefit vector, the only non-zero term is the $\Delta EB_{commercial}$, which is shown in Figure 7.25.

The line *OA* indicated on the figure divides the tradespace into two parts. The alternatives situated on the lower part of the line are the alternatives, which cost more to obtain them and generate less benefit. The alternatives located in the upper part of the line are the ones that generate more revenue that their cost and are more cost effective. The alternatives in the upper part of the line and farthest from the line show the most flexibility.

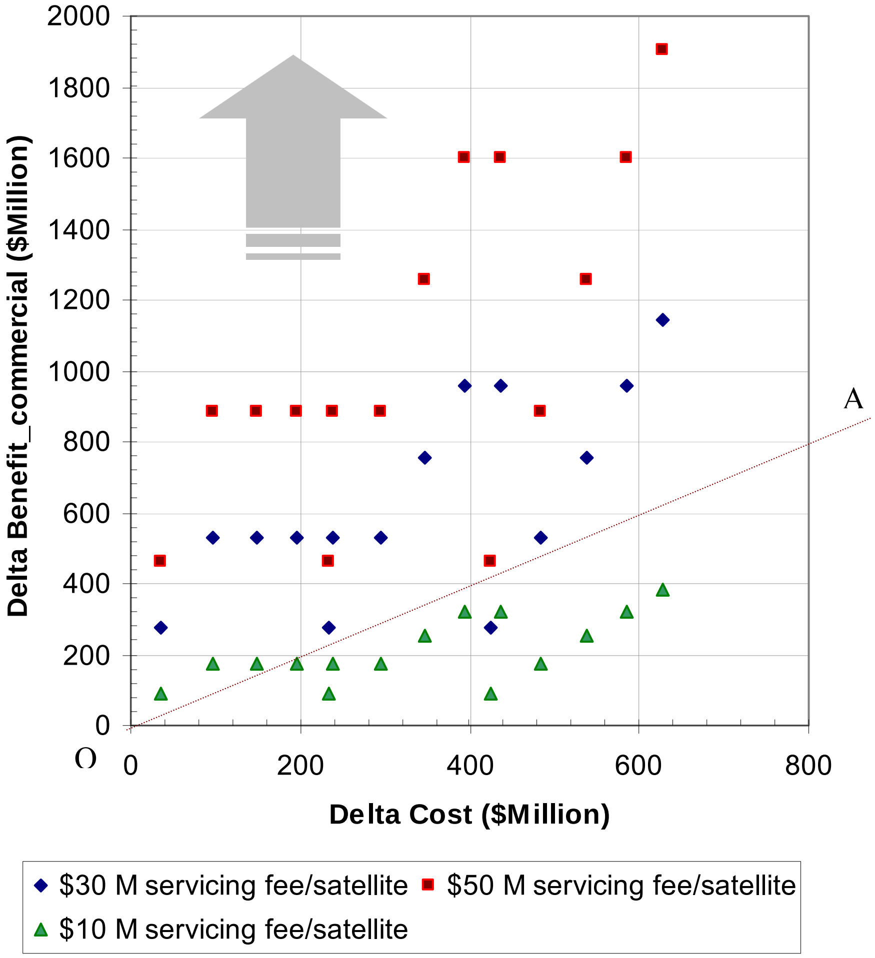


Figure 7.26. Flexibility tradespace for different servicing charges per satellite

It should be noted that $\Delta EB_{commercial}$ is a function of the average price charged per servicing a satellite. The flexibility tradespace in this case study is sensitive to the charged price. Figure 7.26 shows alternatives 1 through 15 for three different charged prices of \$10M, \$30M, and \$50M respectively. As can be seen in Figure 7.26, with an increase in the servicing fee per satellite, a higher percentage of the alternatives enter the cost effective region, which is above the *OA* line. In general, with increase in servicing charge, the alternatives move upward in direction of increased delta benefit in the flexibility tradespace.

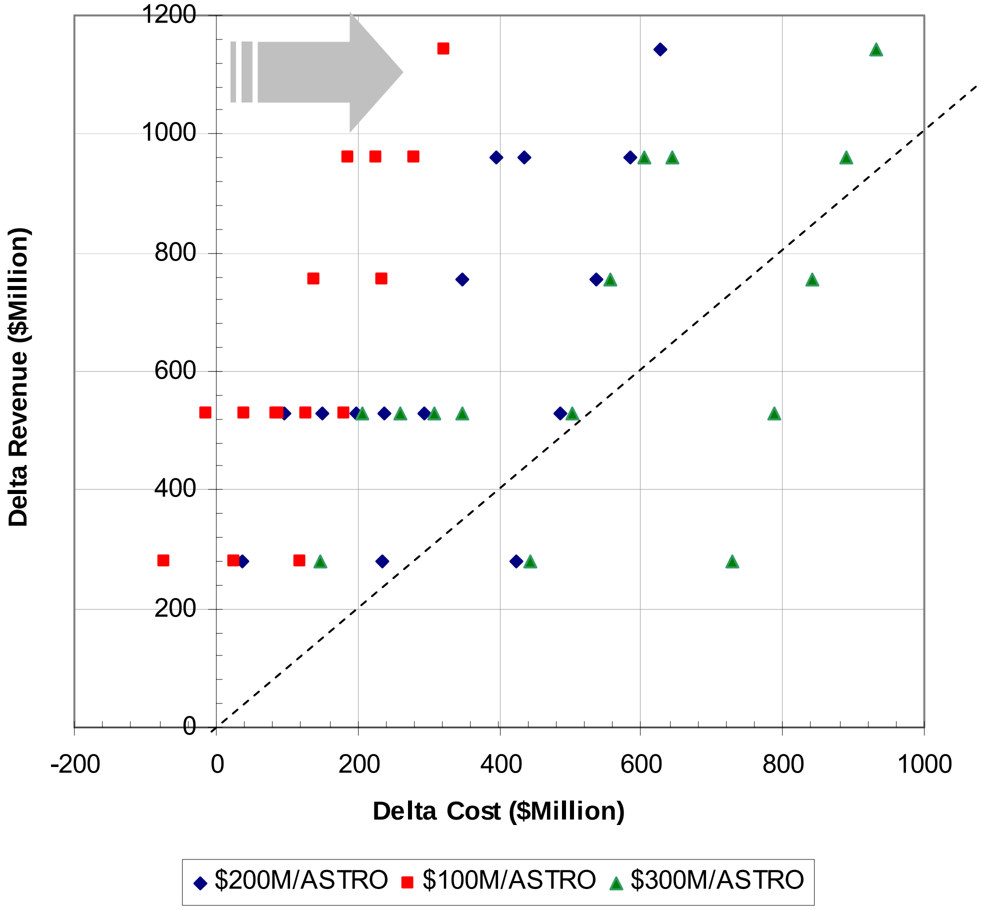


Figure 7.27. Flexibility tradespace for different ASTRO costs

Figure 7.27 shows the flexibility tradespace for the constant servicing charge of $30 million and three different infrastructure costs of $100M, $200M, and $300M per ASTRO respectively. As can be seen, with increase of the infrastructure cost, a higher percentage of alternatives enter the region below the cost-effective line. The delta cost of alternatives are measured with regards to a base case where the cost of an ASTRO is assumed to be $200 million. Therefore in doing sensitivity analysis around the cost of ASTRO, there are some alternatives that are cheaper than the baseline case, and fall within the negative territory of the graph. The major trends and drivers are similar to those explained in Figures 7.25 and 7.26.

Figure 7.28 shows the flexibility tradespace and the satellites serviced per alternative. As can be seen in the figure, the larger sizes of infrastructure can provide more services to the commercial client satellites. The highest number of serviced satellites is for Alternative 15 with an infrastructure of 3 ASTROs and 5 CSCs. Within the three dimensional graph, we can draw a cost-effectiveness plane (instead of the line in previous graphs). Most of the architectures with different numbers of CSCs and ASTROs fall within the cost-effective region of the graph, with the exception of a case where ASTROs outnumber CSCs three-to-one. This would suggest that a capacity limitation of parts for upgrade could render more ASTROs useless. Since one single ASTRO can service many commercial satellites, the number of ASTROs provides less of a constraint than the availability of parts.

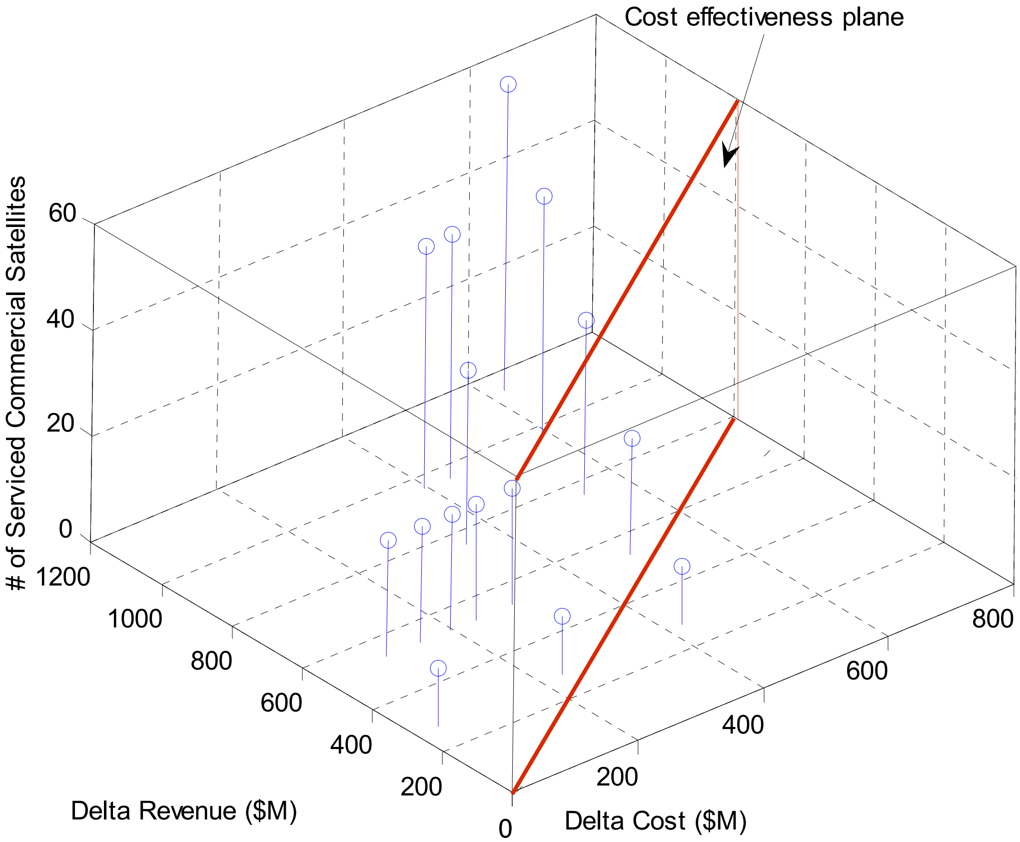


Figure 7.28. Flexibility tradespace and number of serviced commercial satellites for each alternative

The last alternative pertains to servicing the JWST. The expected benefit of servicing the JWST is calculated as follows:

$$EB_{JWST} = 4n_1q_1 + 5pn_2q_2 = 17.5n_1q_1$$

$$\Delta EB_{Alt16} = \left(0,0, EB_{JWST}\right)$$

If the JWST is not serviced, it can only produce $9n_1q_1$ as the benefit. We assume that JWST requires a special ASTRO which carries replacement parts and the required fuel for reaching the L2 orbit and rendezvous and service the JWST. We assume a dedicated ASTRO with a cost 30% higher than the ordinary ASTRO costs for such a mission. The expected cost of this mission will be $260 million. Considering the high original cost of the James Webb space telescope (almost $4.5 billion [JWST 2005]), servicing the spacecraft can be a viable option for improvement of the performance of the space telescope.

Case study 2 leads to some interesting findings:

- The baseline deals with the case of servicing the Milstar satellites. The existence of an Orbital Express infrastructure in geosynchronous orbit creates the opportunity to improve the performance of the Milstar satellites dramatically (80% in case study #2 based on our assumptions).
- With an Orbital Express infrastructure already present in GEO, a large pool of commercial and scientific satellites can be added to the list of client satellites. The commercial client satellites can create an extra income for improvement and expansion of the existing Orbital Express infrastructure in orbit.
- The cost-effectiveness of the servicing to the commercial client satellites is affected by two major factors which include the cost of infrastructure (ASTROs and CSCs) and the servicing charges per commercial client satellite.
- An ASTRO in geosynchronous orbit can be a valuable asset for performing an upgrade and servicing to very delicate and expensive scientific satellites such as James Webb space telescope. With a large cost of JWST (currently $4.5 billion), an ASTRO can provide a relatively cheap way to service and upgrade this valuable scientific satellite.

7.4 Summary

In this chapter, we looked at how the 6E framework would allow the value of flexibility to be taken into consideration in architecture trade spaces. We studied two different cases based on the Orbital Express program. The first case study looks at the flexibility of putting an infrastructure in a sun synchronous orbit and the second case study probes the flexibility of an infrastructure in geosynchronous orbit. Both cases use the same Orbital Express building blocks of ASTROs and CSCs. The ASTROs and the CSCs are currently under development and are being tested in 2006 and will be fully deployed after 2010.

We defined the benefits generated by the different architectures of the Orbital Express program as the increase in benefits to the clients of this program. The Orbital Express program is proposed and funded by DARPA; therefore we assumed that the major clients of such system would primarily be military space systems. The primary and high priority mission of the servicing infrastructure is to service its military client space systems such as ISR-X and Milstar systems in case studies 1 and 2 respectively. Then we looked at the extra benefits that can be achieved by these servicing infrastructures through servicing non-military satellite systems such as Ikonos, Landsat, JWST and a number of GEO commercial satellites. In most cases, the infrastructure needs to be expanded for an extra cost in order to be able to service other scientific and commercial space systems.

We also looked at the issue of refueling for life extension, refueling for maneuvers and upgrading the parts and instruments of the military client satellites in case study #2. Our case study shows that a combination of refueling and upgrading is the most flexible option for the client satellites. Refueling for performing maneuvers does not increase the value and flexibility of the system in comparison with what can be accomplished through upgrading the parts on a satellite. The results indicate that a servicing infrastructure on orbit can create a large amount of flexibility for all the U.S. space systems. ASTROs can also perform tugging, deorbit the old satellites in orbit, and also participate in building larger infrastructures on orbit for NASA for the future Mars and Moon missions. An

Orbital Express infrastructure can help in creating the infrastructure for the next generation of explorers of the solar systems.

In the next and last chapter of this dissertation, we will look at the implications of the 6E flexibility framework and the case studies that were chosen to explore its applications and put this dissertation into the larger context.

References:

(Ball 2004)
Ball Aerospace and technology corp.
http://www.ballaerospace.com/oexpress.html

(DARPA)
DARPA Orbital Express program
http://www.darpa.mil/tto/programs/oe.html

(Dipprey et al. 2003)
N. Dipprey and S. Rotenberger, "Orbital Express Propellant Resupply Servicing," AIAA-2003-4898, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, Alabama, July 20-23, 2003

(Futron 2004)
"How Many Satellites Are Enough? A Forecast of Demand for Satellites, 2004-2012," February 16, 2004, Futron Corporation, www.futron.com

(Hastings and Nilchiani 2002)
D. Hastings and R. Nilchiani. "Developing an orbital transportation network analysis methodology for on-orbit refueling of satellites," AIAA CoreTech 2002 Conference Proceedings.

(Landsat 2005)
Landsat 7 website: http://landsat.gsfc.nasa.gov/

(Lewis 2004)

(MIL 2005)
http://www.designation-systems.net/dusrm/app3/s-7.html

(Milstar 2004)
Milstar Satellite Communications System
http://www.af.mil/factsheets/factsheet.asp?fsID=118

(Potter 2003)
Potter, S., D., "Orbital Express: Leading the way to a new space architecture," Boeing Company, 2002 Space Core Tech Conference

(Stamm et al. 2004)
Stamm, S., Motaghedi, P., "Orbital Express Capture System: Concept to Reality," Proceedings of SPIE, 2004

(Tsien 2003)

W. Tsien, Jacobs Sverdrup, "Advancing Military-Relevant Space Technologies," AIAA-2003-6363, AIAA Space 2003 Conference and Exposition, Long Beach, California, Sep. 23-25, 2003

(JWST 2005)
Big Universe, Tightening Budget: NASA Looks for Ways To Pay for Hubble, Cost Overruns, space news, http://www.space.com/spacenews/businessmonday_050606.html

Chapter 8

8. Conclusion

THIS dissertation dealt with measuring the value of flexibility in space systems. In this Chapter, we will provide a short summary of the discussions in the preceding chapters, explore the validity of the hypothesis, and present the major contributions of this dissertation. In addition, we will discuss the advantages and drawbacks of the proposed 6E flexibility framework and its implications for space systems design and analysis. We conclude by looking at potential future work that could follow the research presented in this dissertation.

8.1 Summary of Dissertation

In the introductory Chapter of this dissertation, we set the context for the rest of the dissertation, with an illustration of the role of flexibility in the potential success or failure of the Galileo spacecraft. We discussed the importance of flexibility and elaborated on the challenge of measuring its value in the design and analysis of space systems. We then presented the hypothesis that a unified framework based on common elements of flexibility could help decision-makers capture different aspects of flexibility and its impact on monetary and non-monetary value delivery of space systems. Chapter 1 also provided an overview of the research methodology used in this dissertation.

Chapter 2 of this dissertation looked at the definitions of flexibility and relevant metrics within the vast field of engineering systems, in which space systems are nested. Exploring the literature of manufacturing flexibility and other technical areas as the primary focus of past scholarship in flexibility, we presented the different measures for flexibility. The most striking insight from this chapter was the extensive overlap between concepts of flexibility and robustness. In addition, most measures that are defined for flexibility are very specialized and geared towards measuring a very specific aspect of flexibility in a particular subsystem of manufacturing, and are not generalizable. The existence of tens of different measures makes the evaluation of flexibility on a system-wide scale difficult, and makes a comparison among different types of flexibility impossible. The underlying ideas for these measures range from deriving flexibility from entropy to using fuzzy logic and abstract mathematics. These measures while highly innovative cannot be applied easily by decision-makers to actual systems, and do not provide information that can be used to integrate flexibility into mainstream design decisions. Studying the concept of network flexibility, we elaborated on the relationship between flexibility and complexity in network systems and pointed to the challenges of measuring complexity in a concrete manner. Therefore, we suggested that the complexity of the system be captured in the cost of building, operating and mitigating the system rather than in an absolute scientific measure that would be less useful to decision-makers.

In Chapter 3 we looked at the state of the art of flexibility in the space systems literature. The study of flexibility in space systems is recent and has been studies for less than 10 years. The study of flexibility in space systems has also had extensive overlap with the concept of robustness, and has mainly entered the field as an emerging need on behalf of large-scale military systems that have faced great uncertainty. Since space systems are costly, take a long time to develop and become inaccessible or hard to access after their launch, the existence of flexibility in such systems is crucial to the success of their mission. Much of the discussions on space systems flexibility focus on on-orbit servicing as an enabler of flexibility for on-orbit assets. The literature covers operation and design, as well as service provider-side versus customer-side flexibility. Reviewing the literature on flexibility in space systems, the general approaches to measuring flexibility have started with applying concepts of economics such as cost per function and elasticity and have evolved to more complex applications such as real options. In this chapter, we discussed each of the proposed metrics for space systems flexibility and elaborated on their applicability and limitations. In the most parts, these metrics are limited to cases where the value delivery of space systems are in monetary form or can be converted in some way to monetary form. There is a general confusion of what methodology to use in what context. For instance, the use of real options for uncertainties that are not market related are inappropriate. There is a lack of a concrete framework that allows decision-makers to measure the value of flexibility in different aspects of their space systems and decide which design actions best suit their purpose.

Chapter 4 is the basic conceptual chapter of this dissertation. Through extraction of the key elements of flexibility from the engineering systems and space system literature, we look at communalities that exist among the different types of measures that have been proposed. The analysis shows that the elements depicted in Figure 8.1 can be considered the key elements of flexibility that can capture many aspects of flexibilities in different systems. Many other elements such as complexity, architecture, policy etc. fall within one or more of these elements. We argued that a comprehensive measure for space systems flexibility should account for these elements. Furthermore, we looked at different cases where each of the above elements were dominant features of flexibility in space systems. An important takeaway from this chapter is the proposition that flexibility is not used to address all types of change in the system; rather it is only geared towards addressing changes that impact the system's value delivery over its lifetime or a fraction thereof.

Based on the insights of this chapter, we develop a comprehensive framework that accounts for the-above-mentioned elements and that can address many aspects of flexibility in space systems.

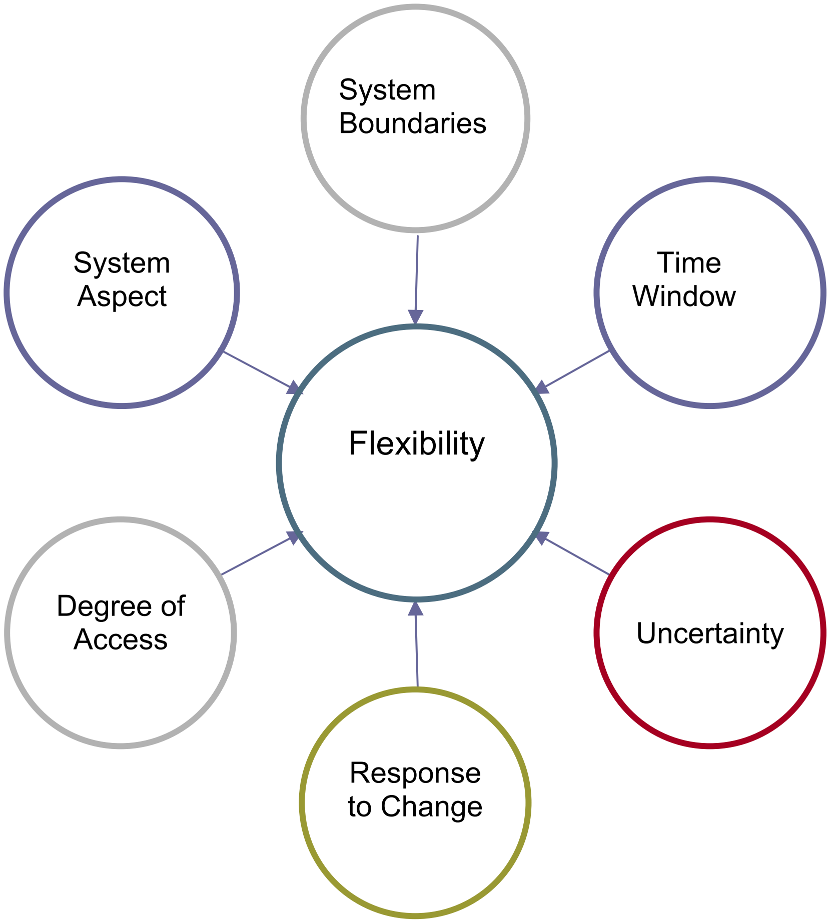


Figure 8.1 Key Elements of Flexibility

Based on the conceptual developments in Chapter 4, we proposed a framework for measuring the value of flexibility in Chapter 5. The 6E framework, so called because of the six fundamental flexibility elements it is based on, provides a guide for decision-makers to measure the value of different aspects of flexibility in their space system. The 6E Flexibility Framework has twelve steps that guide the decision-makers through the process of evaluating flexibility. Figure 8.2 shows an overview of the 6E Flexibility Framework. After discussing each step in detail and with relevant illustrations, we proceeded in proposing how such a framework could be used separately or as part of a multi-attribute trade exploration (MATE) methodology. The 6E Flexibility Framework is unique in that it can measure both monetary and non-monetary value deliveries, making it possible to provide decision-makers for commercial, scientific, and military space systems with the ability to evaluate flexibility based on their preferences for system performance and value delivery.

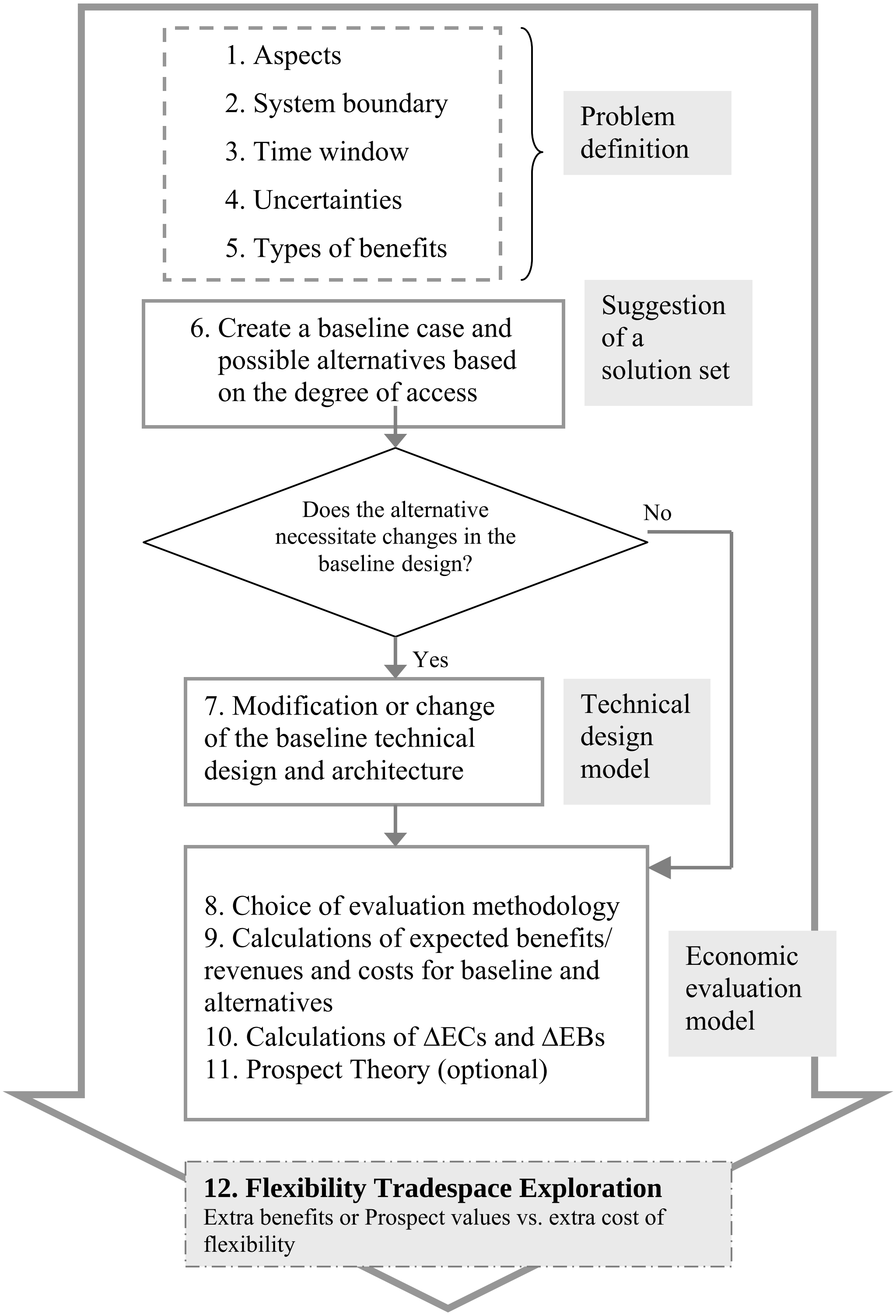


Figure 8.2. The 6E Flexibility Framework

Chapter 6 is the first comprehensive case study chapter of this dissertation, focusing on DirecTV's satellite systems providing satellite television services. It features two distinct case studies that explore flexibility at different levels. The first case study looks at flexibility at the level of a single commercial satellite, DirecTV-8, with regards to capacity expansion and volume flexibility. Looking at existing services provided by DirecTV, we modeled different market segments and their individual market uncertainties. We then looked at the flexibility of alternative designs and decisions in the face of upward market uncertainty. We also looked at flexible alternatives that would perform well in a receding market and compared them in a flexibility trade-space. In the second DirecTV case study, we looked at the fleet of satellites with respect to providing different types of service or mix flexibility. We explored the potential of adding services such as data services, transponder leases in addition to the current satellite television services provided by the company, and its impact on the fleet architecture. For this purpose, market uncertainties were modeled using a binomial lattice analysis approach. The results show that with current transponder technologies providing internet services through DirecTV satellites is not a flexible alternative and would not be financially feasible. On the other hand, in slow markets for satellite television, the leasing of transponders to broadcasting companies can be considered a very flexible alternative.

A major finding of this case study was that improvements that are made in software and data compression techniques are highly flexible alternatives, being far superior to hardware alternatives. This emphasizes the value of software upgrades as a way to increase flexibility in telecommunication satellites. However, software cannot be upgraded indefinitely without a change in the hardware, and is therefore limited to the maximum capacity provided by the existing on-board hardware.

Chapter 7 looks at Orbital Express as a case study and the role of flexibility in its design. Orbital Express is a proposal to provide refueling, upgrading and servicing for assets in orbit using a servicing vehicle (called ASTRO) and a fuel/parts depot (called Commodities Spacecraft or CSC). There are two distinct case studies in this chapter. In the first case study, we looked at an Orbital Express architecture in Sun-synchronous orbit with the aim of providing on-orbit servicing for a cluster of intelligence surveillance and reconnaissance (ISR) satellites. We evaluated the flexibility that Orbital Express would provide for the clients satellites, by providing three types of services: Light refueling (for life extension), heavy refueling (expansion of orbital maneuvering capability), and upgrading surveillance instruments (for better image quality and resolution). In addition, we looked at the possibility of providing services to additional client satellites in the vicinity in the same orbital plane, such as Ikonos and Landsat. The results of this case study showed that light refueling is a flexible alternative, while heavy refueling is not a flexible alternative. Instrument upgrades are also very flexible alternatives. The best alternatives were combinations of light refueling and instrument upgrades in a single mission. In the second case study, we explored at a larger Orbital Express infrastructure in geosynchronous orbit (GEO). While there is an abundance of potential client satellites in GEO, we considered the Milstar cluster to be the primary client of the Orbital Express infrastructure. The services provided to Milstar include upgrading the communications payload and bus electronics. We also considered the addition of U.S. commercial satellites to the client base as alternatives in addition to this base case. Based on projected launches for commercial satellites, we modeled the future trend of the commercial satellite servicing market with the corresponding uncertainties of the telecommunications market. The results of this case study showed that the flexibility of alternatives depends heavily on their willingness to pay for the service and the actual costs of infrastructure. However, it seems that many design alternatives would be flexible as well as economically feasible with the current estimates. At the end, we also explored the servicing potential of the James Webb space telescope, which is to replace the Hubble space telescope and will be situated in the L2 orbit. With the estimated $4.5 billion value of the James Webb telescope, it would be logical to allocate a single ASTRO servicing unit for its servicing. The analysis shows that such an approach it will still be a flexible alternative and should be taken into consideration.

8.2 Validation of the Hypothesis

The hypothesis of this dissertation was that a unified framework based on the fundamental elements of flexibility, such as the 6E Flexibility Framework, could measure the value of different aspects of flexibility in a space system. In the case studies used in this dissertation, we applied the 6E Flexibility Framework for a variety of space systems (commercial, military and scientific) with monetary and non-monetary value delivery, at different scales (satellite level, fleet level), different time windows of change and with regards to different aspects of flexibility (life extension, instrument upgrade, capacity expansion) facing different kinds of uncertainty (technological change and market uncertainty). The four case studies demonstrated the ability of such a framework to provide decision-makers with the information necessary to integrate flexibility in their design and operation decisions and showed that the 6E Flexibility framework could be applied across different aspects of a system easily. Additionally, it was demonstrated how the impact of flexibility on system architecture could be captured in a trade-space analysis using the 6E Flexibility Framework. The power of this framework lies within the fact that it allows different kinds of modeling methodologies for uncertainty, options analysis and trade-space exploration to be combined with technical design processes. Also important is that this framework refrains from assigning weights for different value deliveries, making it possible for the decision-makers to decide on their own how much a particular alternative is valuable to them, rather than convert it to dollar signs that conceal extensive and often shaky assumptions.

8.3 Contributions of this Dissertation

This dissertation provides different kinds of contributions through its literature synthesis, conceptual development of flexibility, methodological development of a bottom-up flexibility framework for space systems and application to two major case studies.

a) Comprehensive literature synthesis for flexibility in engineering systems and space systems

This dissertation provides a unique literature review that spans the fields of manufacturing flexibility, engineering systems flexibility and space systems flexibility.

The scope of the literature review covers 25 major papers in the field of space systems flexibility, more than 60 papers in the field of manufacturing flexibility and 43 papers in the field of systems engineering. Furthermore, it provides an in-depth critique of previous literature in the field of space systems flexibility and explores the merits and drawbacks of existing measures of flexibility.

b) Exploration of conceptual foundations of flexibility

The bottom-up approach of extracting key elements of flexibility through comparisons of tens of existing measures and unifying them into a single set of key elements of flexibility is a unique conceptual contribution of this dissertation. Through this effort, this research unites the existing literature on the basis of common elements that are crucial to the concept of flexibility and its measurement.

c) Development of a unified framework for measuring flexibility in space systems

As previously indicated the methodological contribution of this dissertation is the 6E Flexibility Framework, which enables the measurement of the value of flexibility in space systems. As such, it provides a way for decision-makers to explore whether the value of different aspects of flexibility in their space systems justifies potential upfront investments. While this is beyond the scope of this dissertation, the 6E Flexibility Framework can essentially be applied to many other engineering systems and creates the possibility of cross-comparisons of alternatives that impact the performance of a given technological system in the face of different types of uncertainty. Furthermore, for the first time, this framework allows monetary and non-monetary value deliveries to be taken into consideration within a single framework.

d) In-depth case study of DirecTV

In addition to demonstrating the application of the 6E Flexibility framework, the DirecTV case study features a comprehensive study of the DirecTV satellite enterprise at the levels of individual satellites and the fleet. Through its detailed technical analysis combined with a detailed modeling of the telecommunications market, this case study goes beyond the usual depth of case studies used to explore flexibility and illustrates the value of the 6E Flexibility Framework to take into account important operational details that are crucial but often overlooked in the evaluation of flexibility. In addition, the case study resulted in actual insights for the DirecTV system, including the value of leasing options and software upgrade, and the lack of flexibility for providing data services in case of satellite television market uncertainties. The analysis can be useful for actual DirecTV decision-makers, as well as future academics working on telecommunication satellite systems flexibility.

e) In-depth case study of the Orbital Express

The two case studies dealing with Orbital Express provide valuable information on when and under what conditions the idea of Orbital Express is feasible, and what types of alternative designs can result in higher flexibility of the proposed infrastructure. The case study shows that for servicing ISR's options for increased maneuverability are not flexible, while options for improved instrumentation and life extension can be considered quite flexible. In addition, the case study illustrated that Orbital Express can be quite useful in servicing GEO satellites and expanding its operations to service the James Webb space telescope. Given that the analysis deals with actual systems and actual questions, the results can be useful for decision-makers in DARPA who may be interested to explore different options with regards to the Orbital Express.

8.5 Limitations of the 6E Flexibility Framework

As with any other intellectual contribution of human origin, the 6E Flexibility Framework has limitations in its application. In the following paragraphs, we will look at these limitations in more detail and provide some ideas on how to overcome them.

a) *Challenge in applying the framework to organizational flexibility*: While the basic elements of uncertainty, response to change, time window of change, system aspect, access, and system boundary are applicable to organizations as well as technical artifacts, the framework is specifically developed for more quantifiable types of changes. The measurability of value delivery outcomes in response to change is a basic part of the 6E Flexibility Framework. If this framework is to be applied to organizational flexibility and in general to non-technological flexibility one has to modify the proposed framework.

Therefore, while we can analyze the flexibility of different technical alternatives for DirecTV's systems, we may not be able to evaluate the flexibility of the DirecTV organization and its structure itself. In fact, whether or not any concrete framework for measuring social and organizational flexibility is a matter of potential research for future work.

b) Challenge in application to delayed value delivery or non-quantifiable value delivery
For many public good investments are in the form of dollars, but value delivery is harder to measure. Also important is the fact that many upfront investments may pay off with a lot of delay, or not pay off at all. When the effects of change are unclear, it is hard to assess the value of flexibility, although one can still assess whether or not a system has flexibility.

c) *Delayed costs of implementing flexibility:* If unforeseen costs emerge because of implementing flexibility, it will be impossible to measure them with this framework. In fact this framework takes costs into consideration only if they are a direct (and undelayed) consequence of change.

d) *Lumping complexity with system cost:* At this point the framework considers complexity only when it impacts the cost of the system. Otherwise the absolute value of complexity is not taken into consideration in the framework. There are pragmatic reasons for this, since the measurement of complexity itself is a matter yet to be resolved. However in the long term, we intuitively know that the complexity in the structure and behavior of space systems is inherently interconnected with its flexibility. How this relationship can be taken into consideration is a challenge that should be addressed in the long term.

e) Challenge in applying to unknown unknowns: This framework assumes that we can predict the type of changes that may arise during the lifetime of the spacecraft, but not their timing or their actual magnitude (or for that matter their direction). It can happen that a spacecraft that is designed to be flexible with regards to many known unknowns can end up being totally inflexible when it comes to a change that was entirely not foreseen. On the other hand, a design that we may deem as inflexible with regards to many changes can emerge as flexible when unpredicted changes occur in its environment.

8.6 Future Work

a) Complexity, Flexibility and other System "ilities"

There is a need to explore the relationships between complexity and the value of flexibility as the primary characteristics or "ilities" of an engineering system.

b) Application to Ground Station, Human Resources, Enterprises and Large-Scale Organizations

As indicated, space systems are not just the assets in space, but consist of enterprises, ground stations etc. that have not yet been studied with regards to flexibility. It is important to realize that a large-scale organization like NASA would need to assess how to maximize its value delivery with changing mandates, policy conditions, budgetary constraints and administrative visions. Issues such as human resources and short-, medium and long-term investments in R&D can shape the opportunities that NASA will create for itself in the face of regulatory, market and budgetary uncertainty.

c) Applications to space transportation networks

One of the most promising areas for applying this framework is for space transportation networks and supply chains that can be used for on-orbit infrastructure development and the proposed Human Lunar Exploration missions of NASA.

d) Application to other Engineering Systems

The scope of this dissertation has been limited to space systems, but the 6E Flexibility Framework could potentially be applied to terrestrial transportation networks, telecommunication networks, energy systems, and manufacturing systems.

e) Application to an end-to-end multi-attribute design trade-space

While the methodology chapter and the case studies illustrated how this framework would be used as part of a full-scale space systems design process, it is necessary to apply the framework within an actual design process to explore its merits.

f) Application of Prospect Theory

In this dissertation we shifted the actual evaluation of the flexibilities to the decision-makers. When the preferences of decision-makers are highly non-linear however it is useful to apply prospect theory for eliciting decision-maker preferences. In its current state the framework has been specifically designed to allow for usage of Prospect theory, which is based on evaluating changes in value delivery and cost rather than their absolute values. Such an addition would make it possible for a decision-maker to compare values of flexibility across different product lines and systems.

g) Continuous Flexibility

In this dissertation we focused on discrete changes and responses. A fully flexible system can respond to different foreseen and unforeseen changes by learning through its experience and adapting itself to its new environment. This becomes particularly important for interplanetary spacecraft, which will encounter unknown challenges on their way to explore the universe. An important area of research would focus on continuous flexibility through artificial neural networks and provide the basis for the "conscious" spacecraft that evolves as its environment and goals change.

8.7 A Final Word

This dissertation provided a unified framework for evaluating flexibility for space systems in different contexts and facing different types of uncertainties. It opened the door for studying different aspects of flexibility for various technological systems using a single framework. The framework which was based on six key elements of flexibility extracted from the literature was applied to different case studies and provided a clear-cut way for assessing the value of flexibility for various space systems. There are many challenges, limitations, and shortcomings that have to be overcome for this framework to reach its full potentials, and I look forward to facing and overcoming them all one by one.

“To myself I seem to have been only a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.”

-- Sir Isaac Newton (1642-1727)

Appendix:

Case Study Calculation Spreadsheets

(Based on Relationships Presented in Chapters 6)

A) DirecTV-8 Case Study

u	1.2214				
d	0.8187		Satellite cost	250	$ million
p	0.7218	0.711348595	Satellite op cost/year	25	$ million
p Start	1.00		revenue/year/customer	45	$
Value Start	9.50		Standard deviation	0.2	
v	11.9%		delta T	1	year

Discount rate	10%
delta Y	0.223161377
p	0.721812577

Assumption of increase in market drift based on increase in capability of satellite for broadcasting a larger number of TV channels based on the number of on-board transponders.

growth	Ave. # of subscribers in 2013	# Ku-band transponders
8.0%	28.41	32
8.9%	29.19	36
10.0%	29.98	40
11.2%	30.08	44
12.6%	31.63	48
13.7%	32.48	52
14.6%	33.34	56
15.0%	34.23	60
15.1%	35.14	64

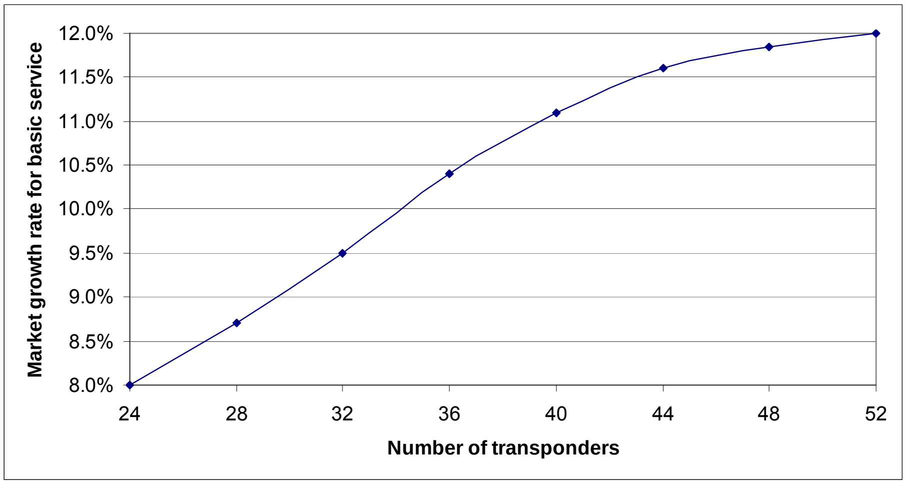
Assumptions on software upgrade

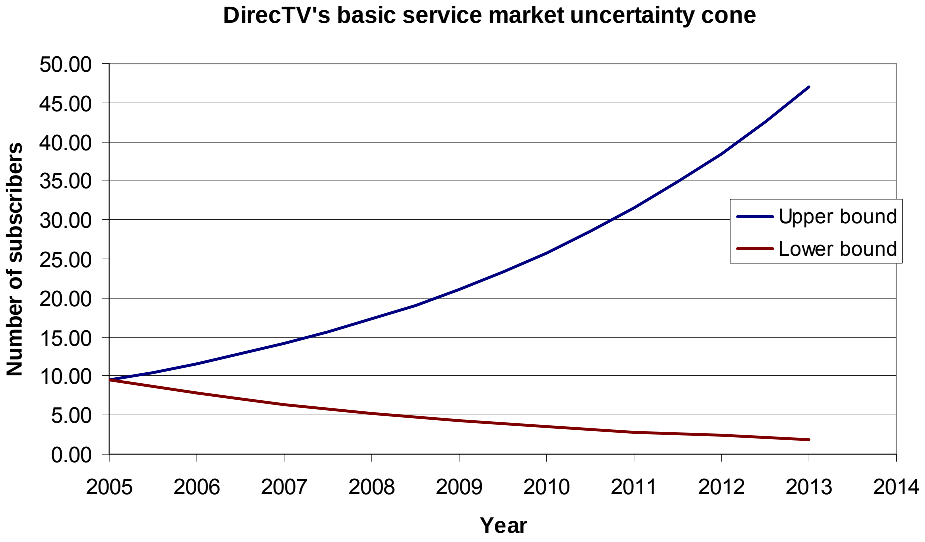
Year 2008	Software upgrade	Probability	Outcome
	p	0.6	1.285714
	q	0.3	1.714286
	1-p-q	0.1	2.142857
	EV(transponder)	1.5	
	revenue	$1,196.73	
	delta revenue	$58.96	
	delta cost	$15.00	

DirecTV-8 Service Expansion Model

Op Cost	$187.34	
Revenue	1181	
Revenue with option after 2008	$1,181	lease
Revenue with option after 2010	$1,181	lease
v	11.9%	drift
Transponder mass for Ku	13.3	kg
power	24.3	w
solar panel mass	0.972	kg
Battery mass	1.215	kg
# of leased Ku-band transponders	0	
lease price for Ku/year	2.5	
extra Ku-band transponder op cost	0	

satellite mod cost	# transponder
-44.4	24
-22.2	28
0.0	32
22.2	36
44.4	40
66.5	44
88.7	48
110.9	52





Outcome lattice for Basic service package

OUTCOME LATTICE (number of subscribers)

2005	2006	2007	2008	2009	2010	2011	2012	2013
9.50	11.60	14.17	17.31	21.14	25.82	31.54	38.52	47.05
	7.78	9.50	11.60	14.17	17.31	21.14	25.82	31.54
		6.37	7.78	9.50	11.60	14.17	17.31	21.14
			5.21	6.37	7.78	9.50	11.60	14.17
				4.27	5.21	6.37	7.78	9.50
					3.49	4.27	5.21	6.37
						2.86	3.49	4.27
							2	2.86
								1.92
9.50	7.78	6.37	5.21	4.27	3.49	2.86	2.34	1.92

PROBABILITY LATTICE

2005	2006	2007	2008	2009	2010	2011	2012	2013
1.00	0.72	0.52	0.38	0.27	0.20	0.14	0.10	0.07
	0.28	0.40	0.43	0.42	0.38	0.33	0.28	0.23
		0.08	0.17	0.24	0.29	0.32	0.32	0.31
			0.02	0.06	0.11	0.16	0.20	0.24
				0.01	0.02	0.05	0.08	0.11
					0.00	0.01	0.02	0.04
						0.00	0.00	0.01
							0.00	0.00
								0.00

Outcome lattice for Premium 1 package

OUTCOME LATTICE

2005	2006	2007	2008	2009	2010	2011	2012	2013
1.50	1.80	2.15	2.57	3.08	3.69	4.42	5.29	6.33
	1.25	1.50	1.80	2.15	2.57	3.08	3.69	4.42
		1.05	1.25	1.50	1.80	2.15	2.57	3.08
			0.87	1.05	1.25	1.50	1.80	2.15
				0.73	0.87	1.05	1.25	1.50
					0.61	0.73	0.87	1.05
						0.51	0.61	0.73
							0	0.51
								0

PROBABILITY LATTICE

1.00	0.75	0.56	0.42	0.32	0.24	0.18	0.13	0.10
	0.25	0.38	0.42	0.42	0.40	0.36	0.31	0.27
		0.06	0.14	0.21	0.26	0.30	0.31	0.31
			0.02	0.05	0.09	0.13	0.17	0.21
				0.00	0.01	0.03	0.06	0.09
					0.00	0.00	0.01	0.02
						0.00	0.00	0.00
							0.00	0.00
								0.00

Outcome lattice for Premium 2 package

OUTCOME LATTICE

2005	2006	2007	2008	2009	2010	2011	2012	2013
2.50	3.55	5.03	7.14	10.14	14.39	20.42	28.97	41.11
	1.76	2.50	3.55	5.03	7.14	10.14	14.39	20.42
		1.24	1.76	2.50	3.55	5.03	7.14	10.14
			0.87	1.24	1.76	2.50	3.55	5.03
				0.62	0.87	1.24	1.76	2.50
					0.43	0.62	0.87	1.24
						0.31	0.43	0.62
							0	0.31
								0

PROBABILITY LATTICE

1.00	0.64	0.40	0.26	0.16	0.10	0.07	0.04	0.03
	0.36	0.46	0.44	0.37	0.30	0.23	0.17	0.12
		0.13	0.25	0.32	0.34	0.33	0.29	0.25
			0.05	0.12	0.20	0.25	0.28	0.28
				0.02	0.06	0.11	0.16	0.20
					0.01	0.02	0.05	0.09
						0.00	0.01	0.03
							0.00	0.00
								0.00

Outcome lattice for International package

OUTCOME LATTICE

2005	2006	2007	2008	2009	2010	2011	2012	2013
0.50	0.67	0.91	1.23	1.66	2.24	3.02	4.08	5.51
	0.37	0.50	0.67	0.91	1.23	1.66	2.24	3.02
		0.27	0.37	0.50	0.67	0.91	1.23	1.66
			0.20	0.27	0.37	0.50	0.67	0.91
				0.15	0.20	0.27	0.37	0.50
					0.11	0.15	0.20	0.27
						0.08	0.11	0.15
							0	0.08
								0

PROBABILITY LATTICE

1.00	0.65	0.42	0.28	0.18	0.12	0.08	0.05	0.03
	0.35	0.45	0.44	0.39	0.31	0.24	0.19	0.14
		0.12	0.24	0.31	0.34	0.33	0.30	0.26
			0.04	0.11	0.18	0.23	0.27	0.28
				0.01	0.05	0.09	0.14	0.19
					0.01	0.02	0.05	0.08
						0.00	0.01	0.02
							0.00	0.00
								0.00

B) DirecTV Case Study #2

DirecTV Fleet model

Transponder mass for Ka	14	kg
power	24	w
solar panel mass	0.96	kg
Battery mass	1.2	kg
Total fleet power	32800	w
Total fleet mass	11642	kg

	Mass	**Power**
DirecTV-8	3800	8500
DirecTV-11	4000	12000
Spaceway 2	3842	12300

	Ka-band transponders	
DirecTV-8	4	
DirecTV-11	40	
Spaceway 2	40	
Total # of Ka-band transponders	84	
Braodband Transponders	0	
Leased Transponders	0	
Alfa	1	
Lease price/transponder	2.5	million

# of broadband transponders		Alfa
	0	1
	10	0.99
	20	0.96
	30	0.91
	40	0.85

Broadband subscribers/trans.	0.01	million
total Broadband subscribers	0.00	million

			2010
Software	p	0.6	1.07
	q	0.3	1.09
	1-p-q	0.1	1.2
	EV(transponder)		1.089
	revenue		3809
	delta revenue		
	delta cost	$40.00	

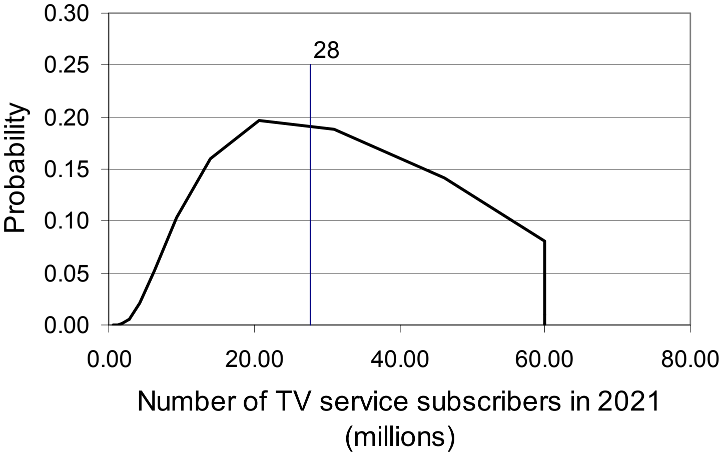
u	1.2214					Discount rate	10%
d	0.8187				$ million	delta Y	0.203
p	0.5791	0.711348595	Satellite op cost/year	40	$ million	p	0.579
p Start	1.00		revenue/year/customer	63	$	DirecTV-8 base cost	250
Value Start	13.90		Standard deviation	0.2		DirecTV-11 base cost	350
v	5.2%		delta T	1	year	Spaceway 2 base cost	300

OUTCOME LATTICE (number of subscribers, not capped)

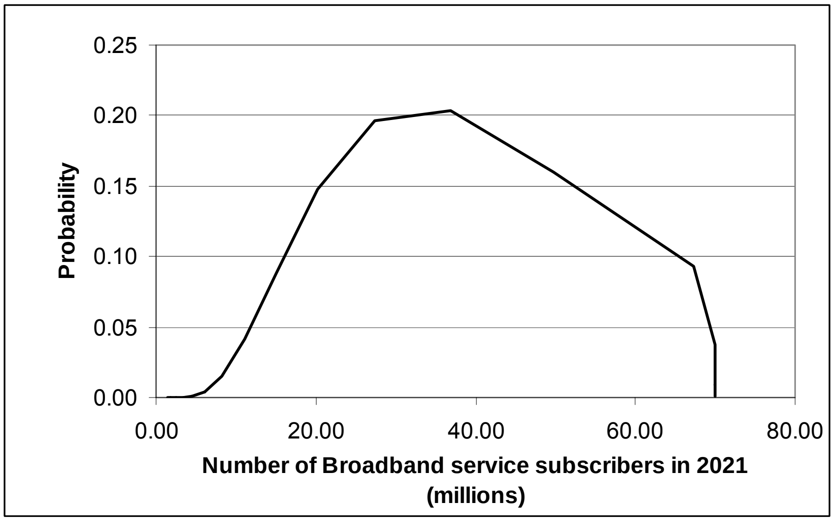
2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	68.85	84.09	102.71	125.45	153.22	187.15	228.58	279.19	341.00
	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	68.85	84.09	102.71	125.45	153.22	187.15	228.58
		9.32	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	68.85	84.09	102.71	125.45	153.22
			7.63	9.32	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	68.85	84.09	102.71
				6.25	7.63	9.32	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15	56.37	68.85
					5.11	6.25	7.63	9.32	11.38	13.90	16.98	20.74	25.33	30.94	37.78	46.15
						4.19	5.11	6.25	7.63	9.32	11.38	13.90	16.98	20.74	25.33	30.94
							3	4.19	5.11	6.25	7.63	9.32	11.38	13.90	16.98	20.74
								2.81	3.43	4.19	5.11	6.25	7.63	9.32	11.38	13.90
									2.30	2.81	3.43	4.19	5.11	6.25	7.63	9.32
										1.88	2.30	2.81	3.43	4.19	5.11	6.25
											1.54	1.88	2.30	2.81	3.43	4.19
												1.26	1.54	1.88	2.30	2.81
													1.03	1.26	1.54	1.88
														0.85	1.03	1.26
															0.69	0.85
																0.57

PROBABILITY LATTICE

2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1.00	0.58	0.34	0.19	0.11	0.07	0.04	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.42	0.49	0.42	0.33	0.24	0.16	0.11	0.07	0.05	0.03	0.02	0.01	0.01	0.00	0.00	0.00
		0.18	0.31	0.36	0.34	0.30	0.24	0.19	0.14	0.10	0.07	0.05	0.03	0.02	0.02	0.01
			0.07	0.17	0.25	0.29	0.29	0.27	0.24	0.20	0.16	0.12	0.09	0.07	0.05	0.03
				0.03	0.09	0.16	0.21	0.25	0.26	0.25	0.23	0.20	0.16	0.13	0.11	0.08
					0.01	0.05	0.09	0.14	0.19	0.22	0.23	0.23	0.22	0.19	0.17	0.14
						0.01	0.02	0.05	0.09	0.13	0.17	0.19	0.21	0.21	0.20	0.19
							0.00	0.01	0.03	0.05	0.09	0.12	0.15	0.18	0.19	0.20
								0.00	0.01	0.01	0.03	0.05	0.08	0.11	0.14	0.16
									0.00	0.00	0.01	0.02	0.03	0.05	0.08	0.10
										0.00	0.00	0.00	0.01	0.02	0.03	0.05
											0.00	0.00	0.00	0.01	0.01	0.02
												0.00	0.00	0.00	0.00	0.01
													0.00	0.00	0.00	0.00
														0.00	0.00	0.00
															0.00	0.00
																0.00



0.30
0.25
0.20
0.15
0.10
0.05
0.00
Probability
28
0.00
20.00
40.00
60.00
80.00
Number of TV service subscribers in 2021 (millions)



0.25
0.20
0.15
0.10
0.05
0.00
Probability
0.00
20.00
40.00
60.00
80.00
Number of Broadband service subscribers in 2021 (millions)