Framework for Evaluating Customer Value and the Feasibility of Servicing Architectures for On-Orbit Satellite Servicing

by

Andrew Michael Long

B.S. Aerospace Engineering
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Submitted to the Department of Aeronautics and Astronautics and the Engineering Systems Division for the degrees of Master of Science in Aeronautics and Astronautics and Master of Science in Technology and Policy
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Author...
Department of Aeronautics and Astronautics
Engineering Systems Division
April 30, 2005

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

Accepted By..
Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program

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

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Abstract

The question that this thesis examines is whether traditional monolithic satellite designs have limited the value that the satellite market generates for the space industry. To answer this question, this thesis focuses on the "Value" that satellites generate. By examining the value that satellites offer their operators, this thesis determines if alternative methods of satellite design offer greater value than traditional satellite designs. One alternative method that is examined is on-orbit satellite servicing. On a basic level, on-orbit satellite servicing is the process of providing services to a satellite in orbit, such as: relocation, refueling, repairs, or upgrades.

The purpose of this thesis is to describe and support a framework for determining the value of on-orbit satellite servicing. The framework involves examining on-orbit servicing as a competitive market and dividing that market into two sides —the customer and the provider. By examining the customer side of on-orbit servicing, this thesis identifies the reasons a customer would require servicing and thus determines the value that can be delivered to the customer. By determining the point where the value of servicing is zero, the customer's maximum servicing price can be computed.

By examining the provider's side of the market, this thesis identifies the different forms of servicing that can fulfill the customer's needs. Based on a provider's forms of servicing, the provider's minimum servicing price can be determined. Finally, by overlaying the maximum servicing price with the minimum servicing price, one can determine if a feasible on-orbit servicing market exists. If any overlap exists, then a feasible range of servicing prices exists and servicing makes sense. Simply put, an overlap represents the case where a customer need exists and a provider has the ability to meet that need – hence a servicing market exists. This thesis concludes with a discussion concerning the development of on-orbit satellite servicing and how this development is not limited solely by economic and technical issues.

It is the purpose of this thesis to show that on-orbit satellite servicing provides a means for escape from the traditional approach of satellite design, thereby allowing a paradigm shift towards more valuable design approaches. While some may believe that on-orbit satellite servicing provides a means to sustain current technology trends, it is argued that on-orbit satellite servicing is a disruptive technology. With disruptive technologies come the opportunities for greater value and dramatic change. On-orbit satellite servicing provides the opportunity for a paradigm shift in satellite design that can lead to dramatic new ideas, uses, and valuations of space.

Thesis Supervisor: **Professor Daniel Hastings**
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Engineering Systems Division

To: Erin, Mom, and Dad

Thank you for all the support

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Chapter 1. Introduction

Since the launch of the first satellite, Sputnik, on October 4, 1957; the applications of satellites have become essential. Today satellites contribute vastly to the world economy and to our daily lives. Satellites provide entertainment in the form of video, help in an emergency using the Global Positioning System (GPS), clear global communications (Voice and Radio), global monitoring (observations and environmental conditions), agricultural savings, continuing education, business investment, cancer research, support for banking and gas stations in the form of secure ATM and credit-card transactions, global internet access where no supporting infrastructure exists, and various other military and scientific applications (Sacknoff, 1999). The applications of satellites and space appear to be limitless. Looking into the future, as the demand for information and global commerce expands, the demand for space technology and its applications will likely increase, thereby creating a continued demand for satellites. This leads to the big question at hand: with the likelihood of increased demand for satellites in the future, is traditional satellite design the best approach?

1.1. Current Problems with Traditional Satellite Design

Despite the possibility of great future demand for space applications, the development and deployment of satellites have a single unifying barrier —cost. It is well known that the deployment of satellites is an expensive task. The typical cost for the launch of a geosynchronous (GEO) communications satellite ranges from \$75 to \$200M (Aerospace, 2002, CBS NEWS, 2002). These high costs pose a real problem for the aerospace industry since satellites historically have a 5-13% failure rate during their operational lives (Sullivan, 2001). Combining this failure rate with the historic 4 to 5% launch failure rate, (Sullivan, 2001) indicates that about 1 in every 7 satellites can be expected to fail before the end of its operational life (Figure 1-1). This high chance of failure could contribute to a slowing-down, or worse reduction, in the demand for future space technologies and applications.

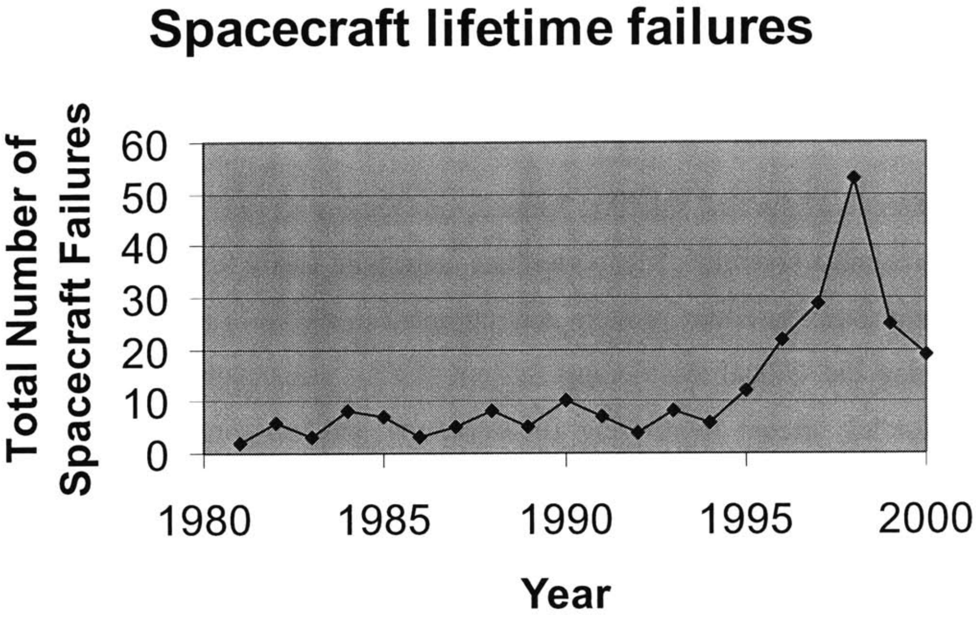
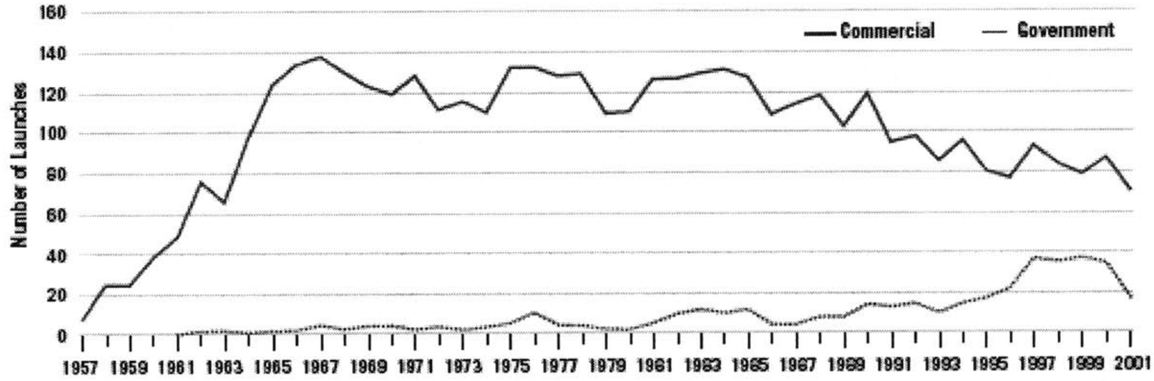


Figure 1–1: Spacecraft Failure Trend (Sullivan, 2001)



Source: FAA

Figure 1–2: U.S Satellite Launch Trends (Aerospace Commission, 2002)

The slow-down or reduction in demand for space applications was strengthened by the shift from a government-based industry to a commercial-based industry after the Cold War. This trend is supported by the clear reduction in overall government launches and increase in commercial launches (Figure 1–2). The shift from the government-based industry to a commercial-based industry has major ramifications for future space applications due to the differences between these organizations and their cultures. As the space industry has shifted towards a highly economic-based industry, the use of space and its applications have been held captive by the traditional economic practices of the commercial world. This shift has switched the focus of space away from innovation and re-centered the focus on investor return. With investor return being the dominant focus of the industry, the real chance of satellite failure (1 in 7) combined with the high cost of space systems has generated a strong risk-aversion within the industry. The risk-adverse nature of the industry has forced satellite designers toward three common elements of design: redundancy, proven technology, and long operational lifetimes. While these design trends may lead to a perceived greater guarantee of future returns, these design trends may not be the best choice if the industry is going to meet the high-paced high demand for space that the future could bring.

1.1.1. Design with Redundancy

A common source of failure in any space system is component failure. Component failure is when a particular subsystem or component onboard the satellite fails due to a design flaw, unknown interaction effect, unintended reaction to exposure to the harsh environment of space, or some other random event. Satellite operators are uncomfortable with the uncertainty about the causes and sources of these failures. The discomfort arises from the additional constraints associated with the use of space that are not associated with Earth-based systems. One of these constraints is the inability to repair the satellite when systems fail.

For the most part, when things go wrong with Earth-based systems, they can be fixed. However, satellites do not have the option of being repaired when things go wrong. With few exceptions, from the moment of launch, human hands will never touch these systems again. Satellite operators have been forced by traditional satellite design to accept that, if and when any space system fails, there is very little anyone can do about it. Thus, in order for the commercially-driven industry to maintain satellite return, satellite operators have placed a large amount of pressure on satellite designers to avoid or at least limit all potential sources of failure. Satellite designers have responded by adding redundancy into satellites in large part to eliminate, or at least minimize, the occurrence of a lifetime failure.

1.1.1.1. What is a Redundant System?

The idea of a redundant system is that in the event that a subsystem or component onboard the satellite fails, the redundant systems will take over the operation of the system that failed. A good example of a redundant Earth-based system is a back-up generator that is used in case of power outages. The purpose of back-up generator is to supply an uninterrupted source of power in the event that the main power system goes down. The downside of a redundant system is that typically the system must be purchased and installed prior to the failure. If the redundant system is complex, then the design of the primary system may have to be redesigned to incorporate the redundant system. The installation of a redundant system can have rippling effects that impact the design of the primary system. These rippling effects can lead to substantial cost increases, unique/non-universal fixes, redesigning of the primary system; etc. Thus, due to the drastic changes that are often required to incorporate redundant systems, it is common to find redundancy only in cases where either the system cannot be repaired or failures are simply unacceptable.

Unfortunately, current satellites are one of these cases. It is not uncommon to see triple, if not more, redundancy in today's space systems due to the high costs and risk-aversion of the industry. While a large amount of redundancy decreases the likelihood of lifetime spacecraft failures, the increased redundancy also leads to a major problem. While redundant systems provide security in the event of a system failure, redundancy results in the design of very complex satellites. As complexity in the satellite increases, production takes longer, potential rework increases, and standardization decreases, resulting in an extremely high price tag.

In theory, the value of a redundant system is only delivered in the event of a system failure. Thus, redundancy adds value to the satellite operator because it allows the satellite to react to potential future failures with intervention. This flexibility to support failure is the value that redundancy offers the satellite operator. But, is redundancy the only way to deliver this flexibility? Couldn't the flexibility to support future failures also be provided if the satellites could be repaired? This raises the question about whether or not satellite redundancy is a more effective method of delivering value than satellite repair.

1.1.2. Designs with Proven technology

In addition to redundant systems, the second way satellite designers have responded to the demand for reducing lifetime failure is through the use of low-risk proven technology. The transition towards a risk-adverse industry has forced satellite designers to take less and less risk. One result has been that satellite designers have been pressured to use more reliable technology in their design of satellites. An example of the designer's reaction has been the development of technology readiness levels (TRLs) by NASA. NASA classifies all technology for space applications on a scale from 1 to 9 based on the maturity of the technology. Although TRLs 5 through 7 indicate that the technology that has been demonstrated, NASA generally requires a TRL of 8 or higher for a technology to be used in space.

The adoption of these types of technology readiness scales, along with the low return on investment (ROI) associated with new technology development, has forced satellite designers towards the use of low-risk flight-tested technology. In the short term, these evaluation scales have had the desired effect: by using proven technology satellite operators have reduced the chance of system failure, thereby reducing lifetime failures. However, the result of long term use of these types of scales and proven technology has lead to negative long-term effects with respect to space-related innovation. Today, it is not uncommon for new satellites to incorporate technology that is almost a decade or more old because of the pressure for low-risk proven technology.

Although the use of proven technology decreases the chance of system failure, it creates a greater problem with regard to satellite performance. By using proven technology, innovation into new more capable technologies is delayed or prevented. By neglecting these new technologies, satellite operators are trading the greater performance that a new satellite design can achieve for the increased reliability delivered by proven technology. Historically, space-based processors have been three or four generations behind commercial off-the-self processors. In fact, a study by the Aerospace Corporation estimates that "the performance of space-qualified electronics has typically lagged by 5 to 7 years behind their non-hardened counterparts (Mayer and Lacoe, 2003)". By forcing the use of time proven technology, satellites are not delivering the maximum amount of performance to their operators. A bigger issue is that the shift toward proven technology appears to be in direct contradiction to the very nature of the aerospace industry, the scientific community, and the military. All of these organizations have historically relied on state-of-the-art technology to maximize satellite performance. This raises the following question: do the known benefits of low-risk proven technology outweigh the potential greater benefits of new technology? Has the industry shifted focus towards minimizing risk as the dominate design element instead of satellite performance? Again, is traditional satellite design the best approach for meeting future demand?

1.1.3. Demand for Long Operational Lives

Finally, the last response to the risk-adverse nature of the satellite industry is the demand for longer operational lives of satellites. As the industry has become dominated by economic decision-making, satellite operators have made decisions concerning satellite design with regard to maximizing their Return-On-Investment (ROI). While the demand for redundancy and proven technology has reduced the failure rate of satellites, the result has been an increase in satellite complexity that has led to higher satellite costs. For example, the cost of a Boeing 601 satellite was once estimated at around $100M, but the new Boeing 702 satellite bus has an estimated sticker price of about $200M. According to a spokesman for Boeing, satellite operators can now expect that the cost of new satellites will be approximately the cost of two older satellites (CBS NEWS, 2002).

The increase in satellite cost, along with the marginal improvements in performance, has lead to the demand for longer operational lives of satellites. The reason for the longer operational lives is that, as the initial price of a satellite increases, it takes longer for the operator to pay-off their investment. Typical break-points on investments in GEO communications satellites do not begin until the 5th to 7th operational year of the satellite's operational life. Thus, due to the shift to an economic-influenced industry the only way to generate acceptable ROI is to require that satellites have a long operational life. Figure 1–3 shows the current trend for satellite operational lifetimes launched over the past decade.

While longer operational lives may be a good short-term solution, in the long run longer operational lives help to reinforce innovation stagnation. Due to the demand for longer lives, satellite designers must incorporate additional redundancy and proven technology to maintain the satellite over the longer period of time. The net effect is that the shift towards an economic-based industry has created a reinforcing downward spiral of increased redundancy, proven technology and longer operational lifetimes. Some may argue that these trends are just some of the early warning signs of the maturity of the aerospace industry. One cannot help but ask, is there a better way to design satellites? Can a paradigm shift in satellite design be adopted such that the industry can meet its investment needs, but at the same time move away from innovation stagnation?

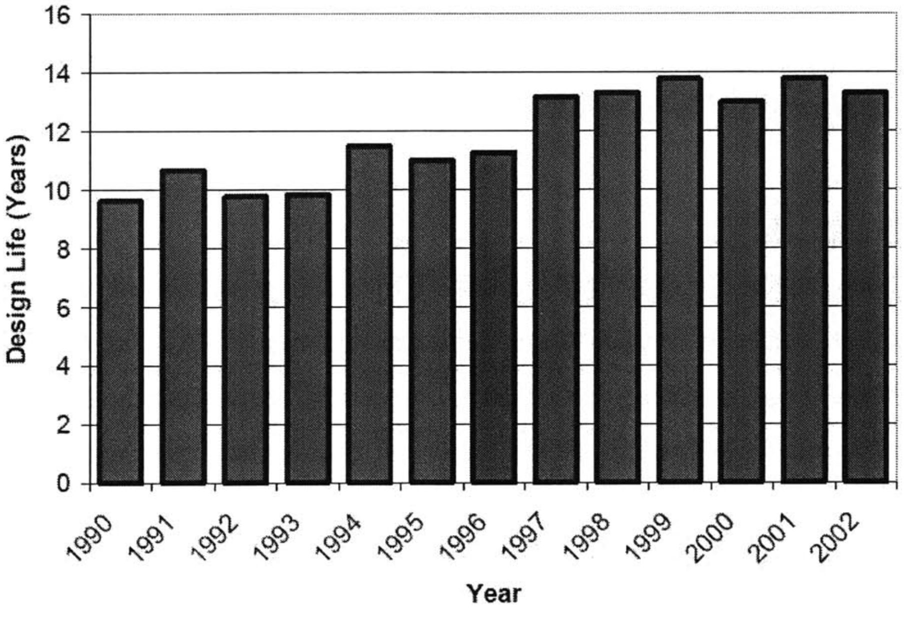


Figure 1–3: Satellite Design Life Trend (Futron, 2004)

1.1.4. Current Dilemma

Is there a way for the satellite industry to escape from the downward spiral of satellite designs that provide long lifetimes, added redundancy, and reliance on proven technology to maximize ROI? The answer to that question is...maybe. To explore alternative options for satellite deign, one must examine the real problem satellites pose for their operators, not the designer's reaction to the operators' needs. The problem with current satellite design is not the high likelihood of failure, but the inaccessible nature of satellites. Everyday systems fail on Earth and they are repaired. It is the accessible nature of the Earth-based systems that allow for the repair. In the case of satellites, inaccessibility of the system is what prevents its repair.

For almost two decades NASA has had the capability to repair one of its most successful scientific satellites, the Hubble Space Telescope (HST). The Hubble was designed to be repaired by astronauts in the event of a systems failure. NASA also designed HST so that its systems could be upgraded as new technology was developed. The ability to upgrade has allowed NASA to greatly increase the performance and return on investment of HST. The general process of repairing or upgrading a satellite on-orbit is commonly referred to as On-Orbit satellite Servicing (OOS).

1.2. <u>What is OOS?</u>

OOS has been studied for over four decades. OOS was first introduced on March 18, 1965 with the first successful Manned ExtraVehicular Activity (EVA). The mission consisted of Alexei Leonov exiting the Voskhod 2 spacecraft and being the first human to step into space (Portree and Treviño, 1997). However, the best known examples of OOS are the four HST repair missions. Each mission sought to repair problems along with installing upgrades. Since the first servicing mission, the performance of HST has been increased by roughly three orders of magnitude due to its serviceable design. While additional cost was incurred to support HST's design and servicing, without a doubt servicing HST has lead to vast increases in investor ROI. As a result of the HST servicing missions, the promise of on–orbit repair, upgrade, assembly, and relocation has drawn great interest from engineers, scientists, and space architects.

In 1999, the Spacecraft Modular Architecture Design (SMAD) study identified six potential benefits of OOS: reduced lifecycle costs, increased payload sensor availability, extended spacecraft orbital lifetime, enhanced spacecraft capabilities, enhanced mission flexibility and operational readiness, and pre-launch spacecraft integration flexibility (Reynerson, 1999). The benefits of OOS seem great. But while OOS has already been embraced by NASA in the case of the HST, OOS has not been embraced by the other sectors of the aerospace industry. Although HST proved that astronauts could service a satellite in orbit, the majority of potential target satellites remain out of the range of the Space Shuttle. Furthermore, the high cost of manned spaceflight combined with the potential risk has made manned OOS next to impossible for the commercial and scientific sectors of the industry.

In response, the focus in OOS has switched from manned servicing to robotic servicing. This shift is not without its own problems. As was stated earlier, the current risk-adverse nature of the aerospace industry prevents the adoption of risky technology. Clearly the technology (particularly space robotics) required for OOS can be viewed as both new and risky. The avoidance of risky OOS technologies is the likely the cause for the resistance in the adoption of OOS by the commercial, military, and scientific sectors. But times may be changing....

Although there was a lack of interest in OOS during the 1990's, a vast amount of research effort was diverted toward investigating the technical issues of OOS. Brief descriptions of each influential research program focused on OOS or its supporting technologies are given below.

1.2.1. Technical OOS issues:

The majority of OOS research conducted over the past decade has focused on the design of servicing infrastructures. By focusing on the "How" of OOS, engineers have identified several technologies required for OOS. These technologies are: autonomous rendezvous and docking, fluid transfer, standard interfaces, space robotics, standardized payloads and satellite buses, and "plug-and-play" satellite design. In 2005, there exist several ongoing research projects focused on the technology required for OOS and the design of on-orbit satellite servicers. The following is a brief discussion of each one of these projects along with the technologies emphasized in each particular design.

1.2.1.1. XSS-10/XSS-11

The Experimental Space Systems (XSS) satellite program is one of the few space-technology-driven research programs in the U.S. Air Force. The XSS program seeks to study future applications and technologies using mini-satellites in a fast-paced 30-month development program. Two satellites programs that have ties to OOS technologies are the XSS-10 and XSS-11 programs. Both of these satellites program seek to evaluate "future applications of micro-satellite technologies that include: inspection; rendezvous and docking; repositioning; and techniques for close-in proximity maneuvering around on orbit assets (Global Security, 2003)." The goal of the XSS-10 program is to demonstrate the complex interactions of line-of-sight guidance with basic inertial maneuvering. The XSS-10 program provides a "stepping stone for future micro-satellite technology demonstrations (Global Security, 2003)." The XSS-10 experimental satellite was launched on 29 January 2003 and successfully performed its 20-hour mission (Figure 1–4).

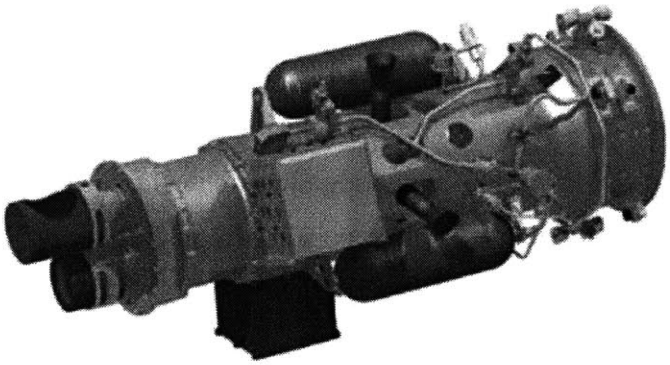


Figure 1–4: XSS-10

The XSS-11 is the second satellite being developed by the Air Force for the purpose of OOS technology assessment (Figure 1–5). The focus of the XSS-11 program is to demonstrate autonomous operations and provide experience with command and control in proximity operations to another space object. To accomplish its mission, the XSS-11 will perform autonomous near object operations with the satellite's second stage. Both the XSS-10 and XSS-11 programs will significantly enhance in-space rendezvous capability, which is essential for all OOS missions.

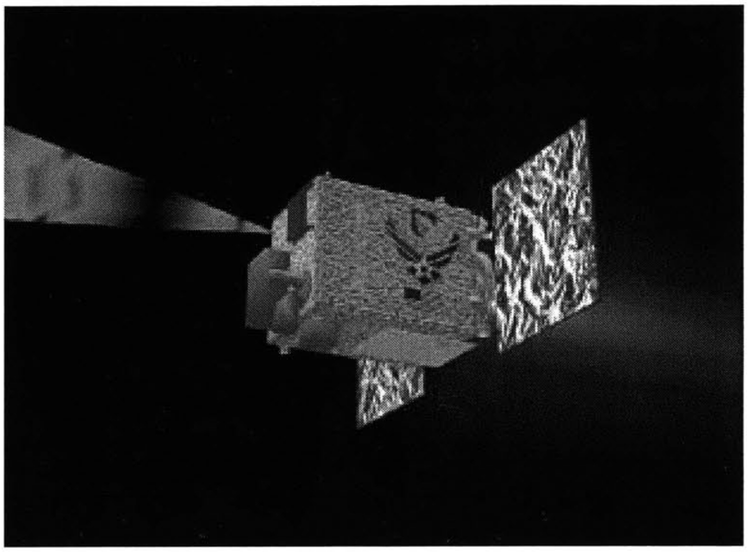


Figure 1–5: XSS-11

1.2.1.2. Orbital Express

The Defense Advanced Research Projects Agency (DARPA) is looking at the development of OOS from a different point of view. DARPA's has teamed with the Boeing Company to work on the Orbital Express program. (DARPA, 2004) The goal of the Orbital Express program is to "validate the technical feasibility of robotic, autonomous on-orbit refueling and reconfiguration of satellites to support a broad range of future U.S. national security and commercial space programs." Orbital Express will focus on vital OOS technologies such as: refueling, electronics upgrades, autonomous rendezvous and proximity operations, and supporting robotics and interfaces. The mission will consist of two satellites: ASTRO and NextSat (Figure 1–6). ASTRO is a prototype satellite servicer in which most of the new technology will be housed. The other satellite, NextSat, will be a prototype of a next generation serviceable satellite. The goal of the mission is for ASTRO to rendezvous with NextSat, transfer fuel and install a new payload. The program seeks to demonstrate a variety of new technologies vital to each step in a typical OOS mission. Orbital Express is scheduled to be tested in September of 2006 with the eventual goal to provide OOS capability for U.S national security space around the end of the decade.

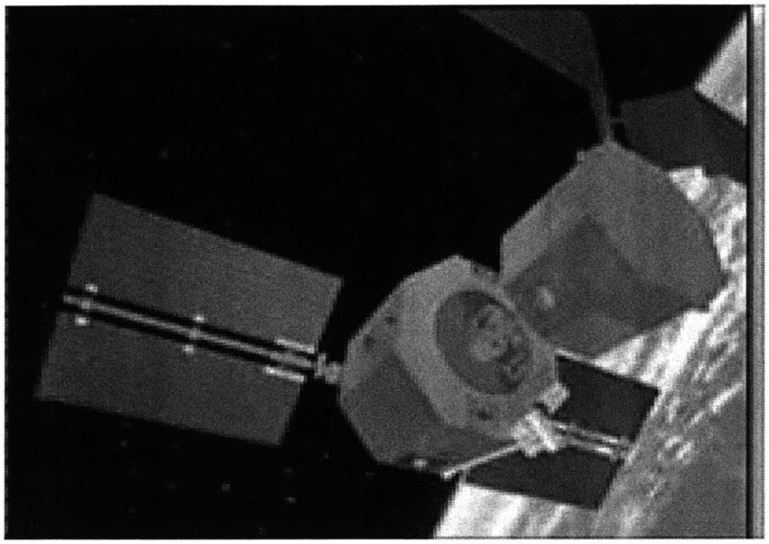


Figure 1–6: Orbital Express with ASTRO and NextSat

1.2.1.3. Hubble Robotic Repair Mission

HST was launched in 1990 and its mission was to look deeper into the universe than was capable with traditional terrestrial telescopes. The most unique design feature of HST was that it was, and remains, the only satellite that was ever designed to be serviced in space. In addition to repairing failed components, NASA claims that each and every time HST is serviced the scientific power of the HST increase by a factor of 10 (Hubble, 2005). Through servicing the HST's usefulness and lifetime appear essentially limitless. HST represents the first step in creating alternative methods to address the inaccessible nature of satellites. Unfortunately, it appears that HST's days are numbered.

Currently, HST is overdue for repairs and upgrading, but the next scheduled servicing mission is in question due to the grounding of the shuttle fleet since the Columbia disaster on February 1, 2003. In light of the guidelines suggested by the Columbia Accident Investigation Board (CAIB) at the time, the former NASA chief Sean O'Keefe repeatedly stated that he would not risk lives to fix the telescope. As a result, all the planned HST repair missions were cancelled. In 2004, a major backlash erupted in the scientific community in response to the NASA chief's decision. Later that year, in response to the scientific community's outcry and congressional pressure, NASA began considering servicing HST using a robotic servicer (Britt, 2004). After an exhaustive search of possible servicing missions, MDR Robotics was chosen to develop a concept for a robotic server. To date no decision has been made concerning the fate of HST, but research into robotic servicing options still continues. Figure 1–7 provides MDR Robotics' current concept for the robotics repair of HST.

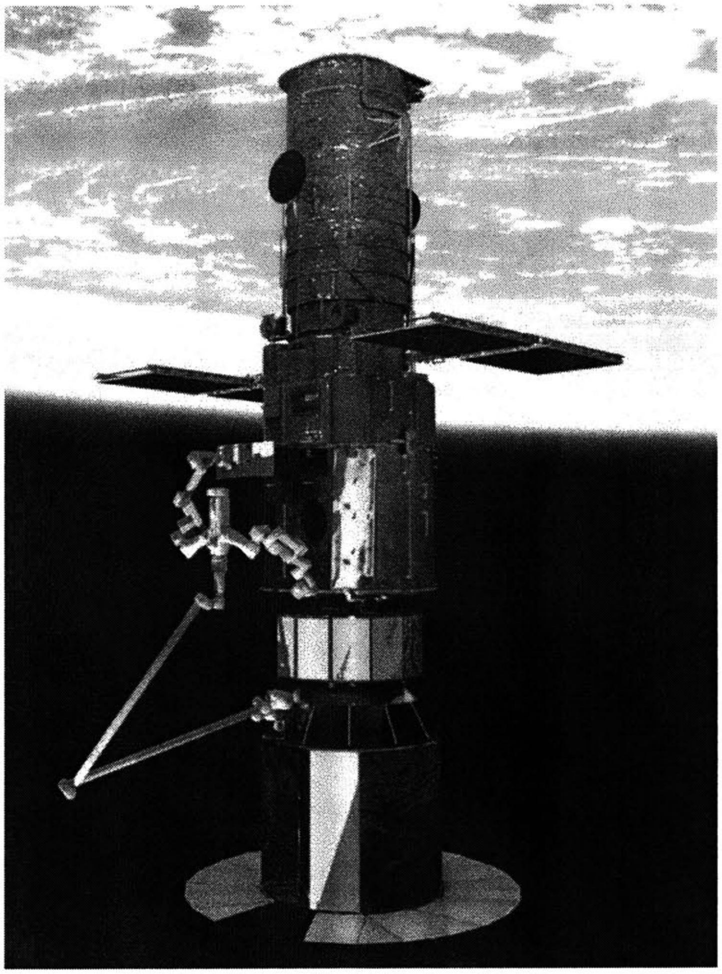


Figure 1–7: Hubble Robotic Servicer Concept (Weiss and Corbo, 2005)

1.2.1.4. ConeXpress

The only fully commercial team pursuing OOS technologies is led by Orbital Recovery Corporation (ORC). ORC's plan is to service a niche market by providing the first commercial-based life extension of satellites by the end of 2008. (ORC, 2004) ORC has focused its market on three-axis stabilized telecommunications satellites currently, or planned, in space. ORC's commercial service is focused on the ConeXpress satellite (Figure 1–8). The ConeXpress will "link up using a special docking system that connects to the telecommunication satellite's apogee kick motor." Once attached ConeXpress is designed to provide station-keeping ability for the target satellite. The concept of the ConeXpress is not to refuel the target satellite, but instead to act as a "Space Tug." ORC expects that by providing additional station-keeping ability ConeXpress can provide up to 10 additional years of operational life.

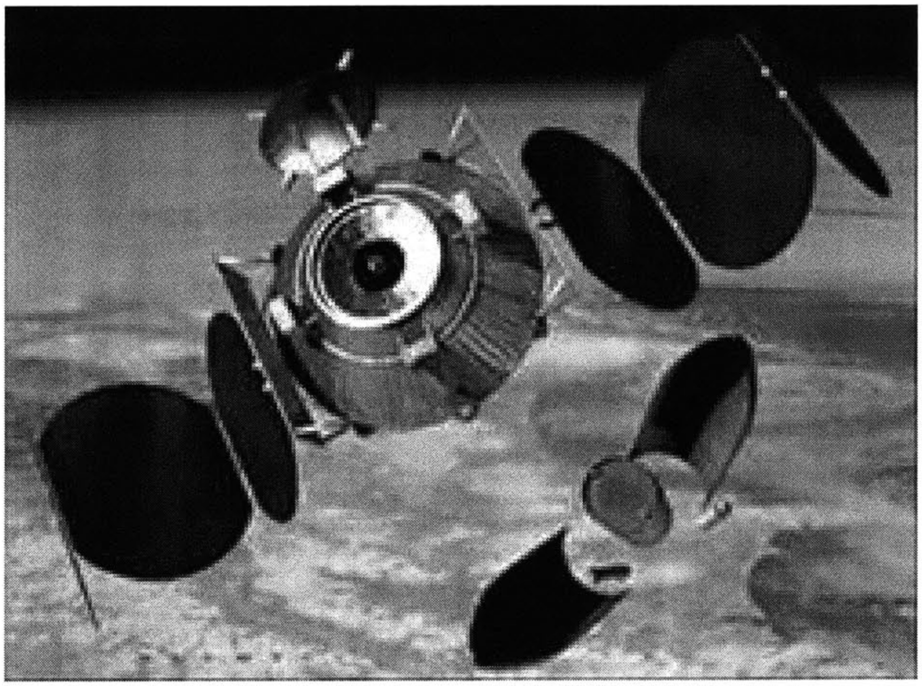


Figure 1–8: ConeXpress

1.2.1.5. Ranger Telerobotic Shuttle/Flight eXperiments

The Ranger Telerobotic Flight and Shuttle eXperiments (RTFX/RTSX) represents the current research program with the greatest legacy that remains directed towards robotic OOS. Both RTFX and RTSX are in development at the University of Maryland's Space

Systems Laboratory (Ranger, 1998), (Ranger, 2002). Initially RTFX was designed to be a free-flying telerobotic servicer capable of repair and upgrade. RTFX was designed so it could mimic most of the tasks that astronauts performed during the HST repair missions (Figure 1–9). The program was put on hold in 1998 when the program encountered funding problems associated the purchase of a launch vehicle. To solve this problem, RTSX was designed. RTSX uses a design similar to RTFX except that RTSX was to be mounted in the Space Shuttle cargo bay (Figure 1–10). To date RTSX is still undergoing testing but delays have resulted in part due to the Columbia accident and reduced funding within NASA. Currently, both RTFX and RTSX remain as one of the most capable servicers designed for OOS. Both servicers are capable of a variety of servicing tasks ranging from simple to complex.

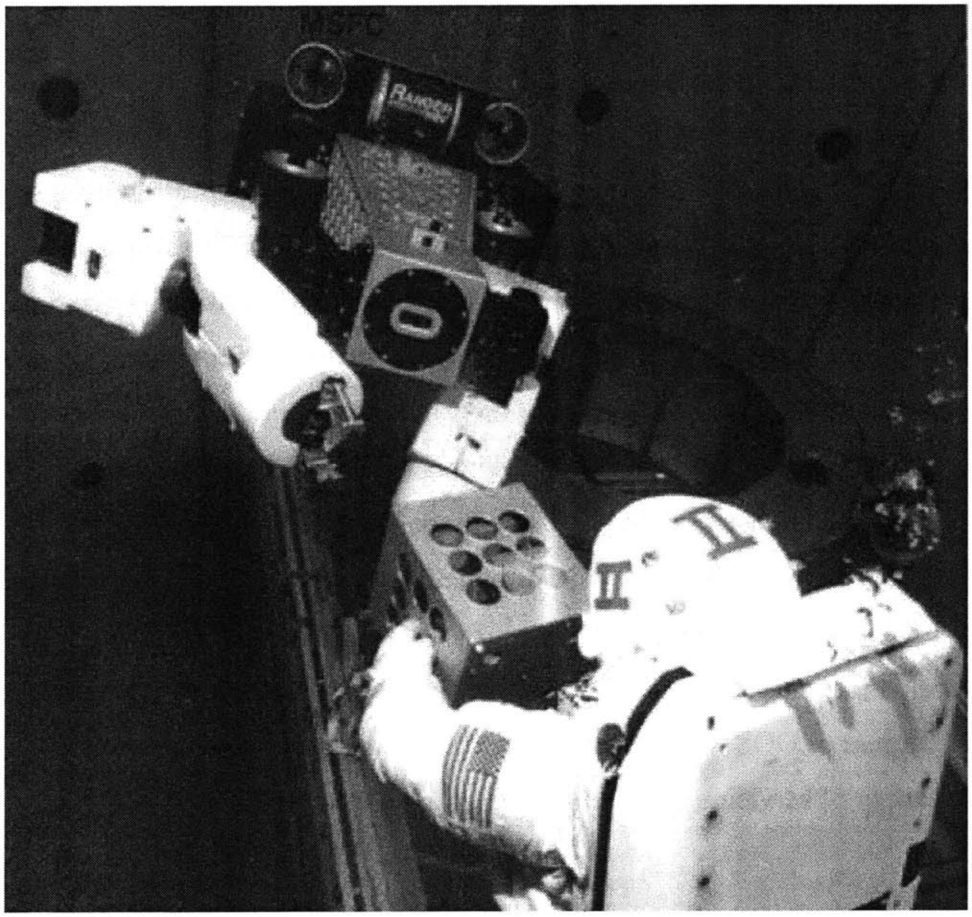


Figure 1–9: RTFX- Neutral Buoyancy Testing (Ranger, 1998)

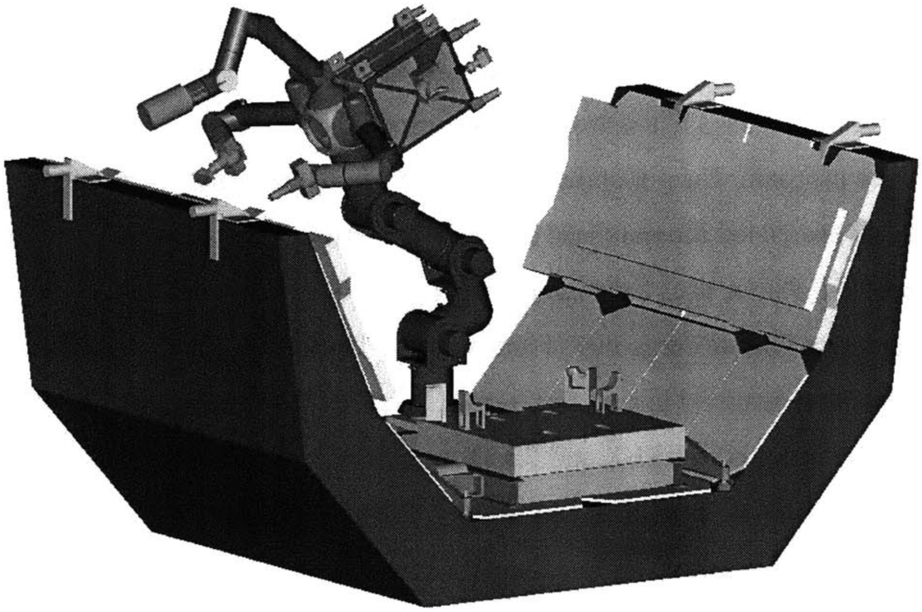


Figure 1–10: RTSX-Mounted Instead Shuttle Cargo Bay (Ranger, 2002)

1.2.1.6. NASA's Robonaut

The final major OOS technology program is the Robonaut program in development at NASA's Johnson Space Flight Center (Figure 1–11). "The Robonaut project seeks to develop and demonstrate a robotic system that can function as an EVA astronaut equivalent….Robonaut jumps generations ahead by eliminating the robotic scars (e.g., special robotic grapples and targets) and specialized robotic tools of traditional on-orbit robotics (Robonaut, 2003)." The advantage of the Robonaut design is that it seeks to mimic the actions of an astronaut in space. To do this the design focuses on the development of a human-based robotic servicer. Since humans have been the only successful way to service satellites in orbit, Robonaut may prove to have an advantage over the other OOS designs. However, it remains to be seen if human interfaces prove to be the best design for serviceable satellites. Either way, Robonaut is a vital program towards the progress of OOS technologies. Like the Ranger program, Robonaut is capable of a variety of servicing tasks ranging from simple to complex.

Figure 1–11: NASA's Robonaut

Each of these programs shows great promise towards the development of OOS. One may then ask; if such great technical programs have been going on for almost a decade, why hasn't a single robotics OOS program been launched?

1.2.2. Why Hasn't OOS Happened?

Many supporters of robotic OOS believe that OOS is being held back due to the technical issues and the risk-aversion of the aerospace industry; i.e. that the reason for the lack of support is the immature state of space autonomy and telerobotics. However, this is not the case. Although support for OOS programs remains low even though promising OOS technology programs exist, the reason for the lack of OOS interest is that the aerospace industry as a whole has failed to define and understand the "why" behind OOS. OOS researchers have been worried about the "how" of OOS and not whether OOS provided more value than traditional satellite design. Simply put, no one has addressed the demand side of OOS; the focus of OOS research has been solely on the supply side of servicing. To make OOS a reality, the industry must first focus on the reasons for servicing (the "why") and worry about the technical issues (the "how") later.

1.2.3. The "Why" Side of OOS

Any assessment of the reasons for servicing begins with looking at the value that is delivered by servicing. Reynerson defines a serviceable spacecraft as any spacecraft for which the value of OOS outweighs the associated cost (Reynerson, 1999). Therefore, a target satellite should only be serviced when the value the satellite's operator derives from servicing outweighs the associated cost. Servicing then represents a method by which the satellite operator can derive additional value from the satellite. In this case, it is reasonable to assume that an operator would only choose to service when the value of servicing outweighs the value delivered by alternative value-generating methods. Because a satellite operator can choose between different methods of deriving value, whether through servicing or alternate methods, the feasibility of OOS can be determined by examining servicing as a commercial (competitive) market.

1.3. <u>Conclusion</u>

The uncertainty and risk-aversion that exists in the aerospace industry surrounding the creation of a commercial OOS service market demands a framework to evaluate potential OOS architectures. This framework must be able to evaluate potential servicing architectures based on the value they deliver to the satellite operator. Saleh states that to determine when OOS is a feasible course of action, the value of OOS must be examined from a customer's (target satellite operator) point-of-view, not the service provider's (servicer) point-of-view (Saleh, 2002). This thesis utilizes the customer-centric model proposed by Saleh to determine the value provided by different forms of servicing and based on these results determines the customer's willingness to purchase the service.

The customer's maximum price for servicing (demand) is determined by determining the point at which a customer is indifferent to OOS versus an alternative method of achieving value. The maximum servicing price creates a range of servicing prices bounded between zero and the maximum servicing price. Next by calculating the provider's minimum servicing price or supply, the feasible servicing range becomes bounded by the provider's minimum servicing price and the customer's maximum servicing price. This creates a feasible range of servicing prices and as a result, a range of feasible OOS markets.

The evaluation process for OOS demonstrated in this thesis consists of five parts:

1) Deriving how servicing can deliver value to the customer
2) Explicitly computing the value that OOS can deliver to the customer
3) Determining the customer's maximum service price
4) Determining the minimum price for which a provider can deliver the customer's desired value (for each potential form of servicing)
5) Determining if a feasible OOS markets exists based on the overlap of the customer's maximum service price with the provider's minimum servicing price.

The overall purpose of this thesis is to provide an understanding of OOS, to define the additional value that OOS delivers to satellite operators over traditional satellite design, and to determine if OOS provides a feasible approach for dealing with the inaccessible nature of satellites.

1.3.1. Thesis Outline

The thesis is divided into nine chapters. Chapter 2 focuses on the first part of the evaluation method. Chapter 2 discusses how OOS represents a commercial servicing market. It shows that, by adopting a commercial market mentality, the service customer's and service provider's points-of-view can be separated and solved independently. Based on this separation, one can adopt the customer-centric framework suggested by Saleh. The customer-centric framework allows one to determine the value that servicing delivers to the service customer independently of the servicing architecture. Chapter 3 discusses the analytical process behind the customer-centric point-of-view for determining customer value. Chapter 3 also describes how to determine the customer's maximum servicing price.

Chapters 4, 5 and 6 provide three examples of determining customer value and the maximum servicing price. Chapter 4 discusses a satellite restoration scenario where a provider extends the operational life of a geosynchronous (GEO) communications satellite. The purpose of extending the operational life of the satellite is the need to maintain the value that the satellite delivers to the customer. In a restoration case, the servicer does not increase the value that the satellite delivers to the customer, but simply restores the value to a previous state. Chapters 5 and 6 examine the case where value is added to a satellite. Chapter 5 focuses on GEO communications satellites, but examines the value that is delivered to the customer through technology upgrades. The purpose of the example is to determine the customer's maximum servicing price with respect to the additional value that can be delivered through satellite upgrades. Chapter 6 also focuses on technology upgrades, but examines the case of a non-commercial customer. Chapter 6 examines the upgrade of the GOES weather satellites and focuses on determining the value that can be delivered through not one, but two potential upgrades. In addition to finding the maximum servicing price, the three examples introduce the reader to the general characteristics of a feasible OOS market. These characteristics can be thought of as guidelines for satellites designers with the goal of creating a feasible OOS market.

Chapter 7 focuses on the provider's point-of-view. Chapter 7 introduces the different forms of servicing and discusses how a service provider can design a servicer to meet the customer's demand for value. Chapter 8 concludes the evaluation framework by defining the process for finding a feasible OOS region and identifies potential roadblocks in the development of OOS. This chapter discusses how the customer's maximum servicing price and the provider's minimum servicing price can be overlaid to define a feasible OOS region. Finally, Chapter 9 summarizes the overall findings of the thesis.

Chapter 2. Defining the OOS Market

For the better part of two decades, the focus of OOS research has been primarily technical. Now that many of the technical issues have been resolved, or soon will be, OOS is being delayed because the industry does not understand the benefits provided by OOS. In addition, the satellite industry has failed to distinguish the reasons for servicing from the methods to provide servicing. The satellite industry needs an understanding of how to map the functions of servicing to the forms of servicing. To provide insight into how this mapping can occur, this chapter examines OOS as a commercial market with servicing being a method by which a service provider can fulfill customer need.

As previously discussed, Reynerson stated that a satellite operator would only want to service a satellite when servicing would provide additional value (Reynerson, 1999). In this thesis, value is considered a function of the benefit that a target satellite delivers to its operator, the risk associated with servicing, the operator's perception of those risks, and all costs associated with operating and servicing the target satellite. In addition to monetary benefits, value can include non-monetary forms such as potential military and scientific observations, the discovery efficiency provided by HST, or the accuracy of weather prediction. An in-depth discussion of value is provided in Chapter 3: Determining the Value OOS Delivers to the Customer. In the current chapter, value will be looked at as a function of the ROI that a satellite delivers to its operator.

2.1. Examining OOS as a Commercial Market

To analyze OOS as a commercial market, the characteristics of the OOS market must be defined. Namely, what type of market does OOS represent, what is being bought or sold, how much supply and demand exists, and how much would a customer be willing to pay for the product or service? There are no correct answers to these questions; no one can predict the demand or how much a customer is willing to spend for a market that does not exist. The lack of answers to these questions creates uncertainty around the definition of an OOS market. This uncertainty in market definition is one of the primary reasons why OOS capabilities have yet to be embraced by the commercial industry.

To understand if a satellite operator would pursue OOS, the value of servicing must first be determined. In order to determine the value of servicing, OOS will be viewed as a commercial market. Traditionally, a commercial service market is the interaction of buyers and sellers or the cross over of supply and demand. For the most part, this definition still holds for OOS, however, the product that is exchanged in the OOS market is not physical, but it is the value that is delivered to the customer. As is common with any commercial market, a customer (satellite operator) always has the option to pursue other means of generating value. In the OOS market, this can be represented by a service provider utilizing different servicing architectures to meet customer demand or a satellite operator pursuing alternative ways of generating value. An OOS market only exists when a servicing architecture can deliver more value to a customer than the customer's alternative value-generating options.

2.1.1. OOS: A Commercial Service Market

What type of market does OOS represent? The market for OOS is not a market where raw materials are turned into goods, components are assembled to make a final product, or a market where goods are exchanged. OOS is a service market. In a service market, the service provider provides a service to a customer at a cost and in turn the service creates value for the customer. Figure 2–1 provides a high-level representation of a potential OOS market. In Figure 2–1, the buyer is the service customer (satellite operator) and the seller is the service provider (OOS provider). Simple microeconomic theory states that any market is comprised of three elements; a buyer and seller, a product, and a price. Pindyck and Rubinfeld explain that no matter the type of business a "market is a collection of buyers and sellers that, through their actual or potential interaction, determine the price of a product (Pindyck and Rubinfeld, 2001)." To establish if an OOS market exists, one must determine if an appropriate price of the product exists for both the buyer (satellite operator) and the seller (service provider). The appropriate price of the product is found by the intersection of the supply and demand curves for that market. As a result, supply and demand curves must be established for OOS to determine if a market exists. This step is this focus of Chapter 8.

2.1.2. OOS Demand: The Customer

The demand side of servicing can be examined as the additional value that is delivered to the satellite operator. The right side of Figure 2–1 relates to the satellite operator. In the OOS market, the satellite operator seeks to purchase a given amount of value. Based on that value, the satellite operator has a maximum servicing price for which he will purchase that value. For any price above the maximum servicing price, it is assumed that servicing will not be the most valuable strategy, i.e. supply does not intersect satellite operator demand. The most important aspect of Figure 2–1 is that the customer's decision process is entirely independent of the service provider. The only aspect of the service provider's architecture that influences the satellite operator's decision is the value delivered from servicing.

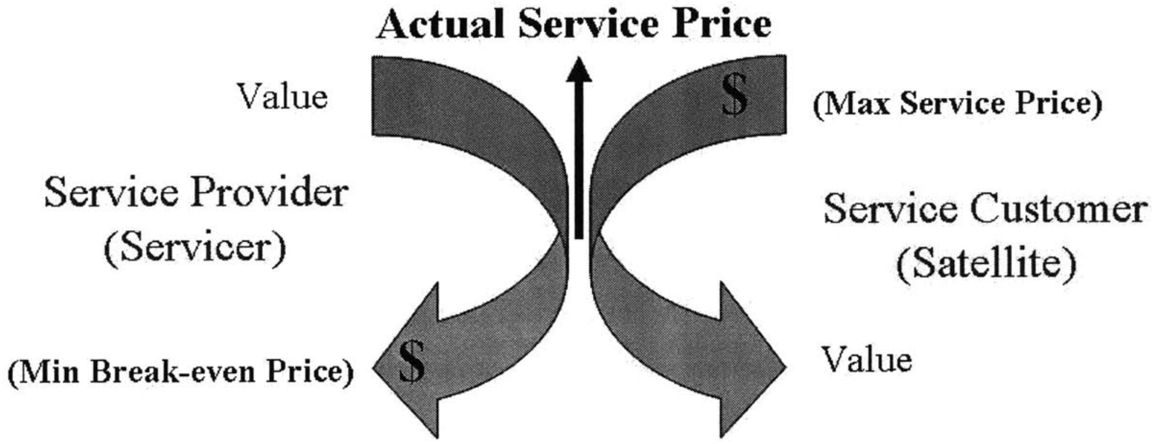


Figure 2–1: Pictorial of On-Orbit Satellite Servicing Market

2.1.3. OOS Supply: The Supplier

The supply side of OOS can be viewed as the service provider's servicing architectures that attempt to satisfy customer demand. The concern of the provider is to provide value to the customer at an appropriate servicing price. Based on the provider's servicing architecture, a minimum servicing price exists for each level of the satellite operator's demand. It is assumed that it is not advantageous to the service provider to provide the service to the customer at a price below the minimum servicing price. In all likelihood this can be represented as the point at which the provider's cost of servicing exceeds the revenue received from the customer. However, this is not the only possible definition for the minimum servicing price.

A provider's minimum servicing price could also be set according to other economic strategies, such as network externalities. In the case of network externalities, a service provider could set their minimum servicing price at such a low price to drive off competition and capture a large network of users. Under this strategy, the service provider would lose money at first but, after a large user base was established, the service provider could supply additional services. For example, initially a service provider could charge extremely low prices for satellite refueling; but, after a large customer base was established, the service provider could charge for other services such as satellite repair or upgrade. By adopting the idea of a competitive market, a service provider can set their minimum servicing price according to any number of economic strategies.

Whatever strategy the service provider chooses, the service provider must be able to offer a servicing price below the customer's maximum servicing price. To establish an appropriate servicing price, a service provider has different servicing methods to consider, each representative of a different servicer design. A unique minimum servicing price is associated with each servicer design. Thus, a service provider is left with a single demand curve and the potential for multiple supply curves. The goal of the supplier is to then determine which supply curve creates the largest range of servicing prices.

2.2. Determining the Price of Servicing

The focus of any market evaluation is to understand the interaction between the buyer and seller in order to determine an appropriate price for the product. The interaction of the service customer and the service provider determines the actual servicing price associated with providing a given level of value to the satellite operator. Precisely mapping the interaction between customer and provider to determine the appropriate price of servicing is very difficult, if not impossible for a market that does not exist. However, based on Figure 2–1, the actual servicing price must exist between the customer's maximum servicing price and the provider's minimum servicing price or a feasible OOS market would not exist.

Examining OOS in this manner provides a clear distinction between the two sides of the market. On the supply side of the market is the service provider. This side has been the focus of the various technical studies conducted over the past two decades. On the demand side of the market is the satellite operator along with their decisions with regard to servicing. The demand side of the market has not been examined and represents the critical roadblock in the adoption of OOS by the aerospace industry. By focusing on the supply side of OOS, previous studies have created feasible solutions for a fictional market. To determine if OOS creates a feasible market, the demand side of the market must be understood.

Determining customer demand (value) is not entirely an uncharted region in the evaluation of OOS. In his Ph.D. dissertation, Dr. Joseph Saleh introduced the idea of a customer-centric framework for the evaluation of OOS (Saleh, 2002). Saleh states that by focusing on only the customer, the value that OOS delivers to the customer can be evaluated. Because value is a customer-driven attribute, the customer will make the decision to service based on the value servicing delivers and not on the form of servicing architecture. It is this separation of the market that allows for the evaluation of OOS. Before using Saleh's customer-centric framework to determine the value of servicing, an understanding of customer value is essential.

2.2.1. Understanding the Customer's Perspective

Minimal emphasis has been placed on understanding how a target satellite can generate additional value and how the need for this value maps to OOS. The foundation of any service market begins with understanding the customers, their values, and their need for ways to derive value. In the case of OOS, the ways in which a provider can deliver value to a customer can range from simple to complex servicing tasks. However, the customer is only concerned with the additional value that can result from the service, not the servicing method. Assuming that the customer will make decisions based on value, a customer will be indifferent between servicing methods as long as all methods provide the same value.

This point is illustrated by the following example of the automobile and a gas station. See Figure 2–2. The automobile market exists because it fulfills a customer's need to go from one location to another in an efficient manner. The automobile owner's need to maintain, or restore, the ability of the vehicle to generate value is satisfied by purchasing fuel from a gas station. Providing fuel to the vehicle in turn restores value for the automobile owner. However, a customer can restore value by calling a tow truck to tow their car, pushing the car themselves, or purchasing a new car with fuel. It can be assumed that an automobile owner values their ability to travel and therefore an owner is only concerned with the amount of fuel that must be purchased to restore the ability to go to the next location. It can safely be assumed that, in the case of an automobile and a gas station, an automobile owner is concerned with the amount of fuel that must be purchased and not the way in which that fuel was brought to market.

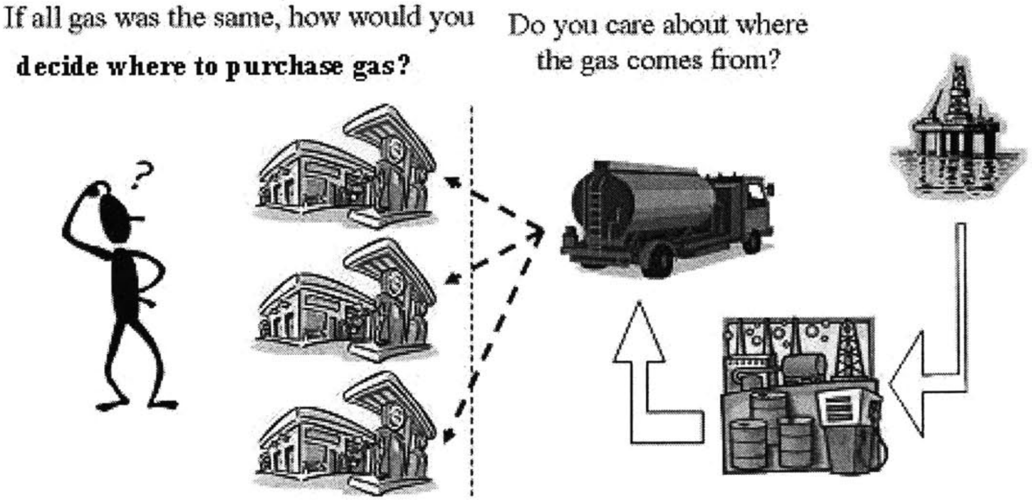


Figure 2–2: Conceptual Example of the Separation between the Customer and Provider Perspectives

Next, if one assumes that all gas on the market is equivalent, it is reasonable to assume that the customer will be concerned with the amount of fuel purchased and the price paid for that fuel. This idea is depicted on the left side of Figure 2–2. In choosing where to purchase the gas, the customer will not be concerned about where the crude oil was extracted, how the oil was refined into gas, how the refined gas was sent to the gas station, or how the gas station operates. In Figure 2–2, the customer's view of the gas station does not extend beyond the dashed line; the customer does not see how the gas station obtained the gasoline. Due to the lack of transparency, the source of the gasoline does not come into play in the customer's decision to purchase gas. If one accepts this logic, a customer would be indifferent to the choice of the gas station and would choose based only on price. This same logic can be applied to OOS. If multiple forms of servicing provide the same value to the satellite operator, the satellite operator will choose between the various forms of servicing based on the servicing price.

When a given form of service experiences a change in the servicing price, the demand for that form of service is affected. In the case of multiple forms of service, the increase in price for one form of servicing will increase the demand for an alternative form of service. When this occurs, the forms of servicing are said to be substitutable. Substitutable forms of servicing allow the satellite operator to choose based on the price of servicing because the value that is delivered by the forms of service is substitutable. The substitutable nature of servicing architecture reinforces Saleh's customer-centric approach to the valuation of OOS by removing the servicing architecture from the decision to service and allowing the satellite operator to decide solely based on price.

2.3. How On-Orbit Servicing Provides Value

In general, the purpose of OOS is to provide additional value to the satellite operator that could not have been provided otherwise. In past studies, many authors have written about servicing architectures and different forms of servicing methods and how these designs provide value to the customer. However, first there is a need to understand why a satellite operator would choose to service in the first place. The answer lies in how OOS can provide additional value to the customer. There are four fundamental functions by which OOS can provide additional value to a satellite operator. These functions are: 1) asset assessment, 2) asset re-organization, 3) asset restoration, and 4) asset augmentation.

The four fundamental functions of servicing are customer specific (i.e. associated with the right side of Figure 2–1). Chapter 7 will discuss how the various forms of servicing (Left side of Figure 2–1) map to the customer's fundamental functions of servicing.

2.3.1. Asset Assessment

Many case studies indicate that satellite operators have the potential need to assess the state of their satellite. This assessment can include understanding how the satellite is operating, where the satellite is, and the physical state of the satellite. Note that the form in which assessment is achieved is irrelevant. All that matters is determining the state of the satellite. An example of assessing the physical state of a satellite would have been determining whether or not damage existed on the Space Shuttle Columbia before the shuttle re-entered the Earth's atmosphere. Although assessment of the physical state of a satellite may not include delivery of a service to a specific satellite, the assessment delivers information concerning that satellite to the operator and thereby generates value.

2.3.2. Asset Re-organization

Re-organizing a customer's asset consists of reorganizing the relationship between the target satellite and the satellite's immediate network for the purpose of increasing customer value. The most common form of asset re-organization is the physical relocation of the customer's satellite(s) to another orbit, independent of the method used to accomplish the relocation. Possible reasons for relocating a satellite could be to provide satellite service to a more profitable market or to decommission a satellite to a graveyard orbit to accommodate a replacement satellite.

Another form of asset organization would be the physical re-organization of a constellation of satellites. Consider the example of a constellation of satellites used for interferometry. A servicer could increase/decrease the distance between the satellites within the constellation, thereby changing the aperture. Aperture size of a satellite constellation directly affects the performance of the constellation and therefore changes in aperture can lead to increases in the value generated by the constellation. Thus, the goal of asset re-organization is to increase the value the satellite provides to its operator without the need to physically alter the satellite.

2.3.3. Asset Restoration

Satellite restoration consists of restoring the value of a satellite or satellite constellation to a previous operating state. Two cases of restoration are repair and life extension. In the case of repair, a customer needs to repair a failure or malfunction so that the value generated by the satellite can be restored. Restoring a satellite's value through repair could consist of mechanical manipulation of the satellite, replacement of failed components, upgrade of failed software, etc. An excellent example of asset restoration is the replacement of the HST gyros. Replacing the gyros of the HST allowed the telescope to resume normal operations, but the service did not provide value beyond what was expected by its operators.

In the second example of restoration, life extension, the satellite's value is restored by preventing a customer's value stream from diminishing due to the decommissioning of the satellite. By extending the operational life of a satellite, the value provided by the satellite can be continued into the future; hence, life extension restores the value provided by the satellite that would have otherwise been lost. The aim of asset restoration is to restore an asset's value to a previous state.

2.3.4. Asset Augmentation

In asset augmentation, OOS adds value for the customer by increasing the capability of the satellite. Capability can be added to a customer's satellite in three ways: 1) a unit-value increase, 2) a unit increase, and 3) a combination of unit-value increase and unit increase. A unit-value increase includes augmenting a satellite with new technology, modifying a piece of existing technology, or upgrading components of the satellite. An example of new technology would be a modification to an imaging payload that allows the payload to be able to view more of the visible spectrum. By increasing the range of visible spectrum, the service increases the capability of the payload that in turn filters down to the customer in the form of additional value. What makes a unit-value increase unique is that the increase in capability provided by the service can be distributed to each of the value generating units (payloads) onboard a customer's satellite. Through a unit-value increase, asset augmentation increases customer value by increasing the capability of each value-generating unit onboard the customer's asset.

The second way to increase a satellite's capability is by increasing the number of value generating units, or payloads, on a given asset. In the case of a geosynchronous (GEO) communications satellite, a customer could increase the number of antennas or transponders, thereby increasing the data rate associated with the satellite. A unit increase affects the customer's value by adding capability through additional units; this form of service does not affect any existing value generating units already in place. Finally, a customer's asset can be augmented through a combination of both unit increase and unit-value increase. A combination approach allows the customer to apply new technology to each value-generating unit onboard, as well as directly increase the number of value-generating units.

With this understanding of the fundamental functions of OOS, the next step is to understand the process by which a satellite operator chooses to service their satellite.

2.4. Deriving Value from Future Uncertainty

Markets can change, components can fail, and new laws can be passed. All of these events can affect customer value. Having the flexibility to react to future uncertainty is how OOS generates value. Saleh et al. point out that "In a world of certainty, flexibility has no value." (Saleh, et al. 2003) By not designing for serviceability, a customer has locked in their future decisions and limits their ability to react to future uncertainty.

OOS delivers value by creating flexibility for a satellite to react to future uncertainty. Customers gain value from their ability to choose between servicing or not servicing, when future uncertainty has been resolved. Previous work has defined the value of OOS as the difference between the expected value of a serviceable satellite and the expected value of a non-serviceable satellite. (Saleh, 2002), (Lamassoure, 2001), (Joppin, 2004)

But, this definition of the value of OOS is not entirely accurate. The true value that servicing provides the customer is the difference between the expected lifetime value with servicing and the expected lifetime value with the next best alternative form of generating value. Why? At some point the price of servicing will be too high and the customer will choose the next best alternative option. The point at which the price of servicing makes the customer indifferent to servicing versus the next best alternative is the customer's maximum servicing price. For any servicing price above the customer's maximum servicing price, the customer will choose the alternative option and the value of servicing will be zero. Therefore, the value of servicing must be defined with respect to a customer's next best alternative options. The customer's maximum service price is then found by determining when the value of servicing is zero.

2.4.1. Customer's Decision to Service

After a service provider determines which fundamental function of servicing will generate value for the customer, the next step is to explicitly determine that value. To determine the value servicing can provide a customer, the customer's decision process with respect to servicing must be examined. For servicing to be a possibility, either the target satellite must be designed to be serviced or the servicer will have to be designed to service a satellite that was not designed to be serviced. Understanding these distinct options and determining which method provides the most value to the customer is the focus of this section.

2.4.1.1. Two-Part Decision: Design Serviceable Satellite

In many OOS cases, a customer will have the desire to restore or augment a satellite. Under these circumstances, a customer must design a serviceable satellite. The question becomes how to the design a serviceable satellite. Reynerson states "the most cost effective way to design a serviceable architecture is to establish the requirement at the beginning of the acquisition program." (Reynerson, 1999) Turner agrees with Reynerson's belief and states "servicing can be used to make large profits by enabling spacecraft to be redesigned to increase revenue generating capacity, not through reduction of spacecraft fabrication and launch costs." (Turner, 2002) It is assumed that in order to develop a serviceable satellite, satellite operators must initially demand that their satellites be designed for servicing from the beginning.

Under this assumption, the customer's decision to service becomes a two-part decision analysis. The satellite operator first decides whether or not to design the satellite for servicing. If an operator decides to design for servicing, the operator can later decide whether or not to service the satellite. The operator will make the decision to service as long as it provides additional value. If the satellite operator decides not to design a serviceable spacecraft, the operator's choices are limited. The operator still has alternatives for generating additional value, but OOS is not one of them.

Figure 2–3 displays a simplified version of the satellite operator's two-part decision model. The upper branch of the decision tree represents the decision path available to a satellite operator that has decided not to design their satellite for servicing. Notice that in this branch the operator does not have the option to service the satellite; the operator's future options are either decommission, do nothing, or replacement. The upper branch of the decision tree represents the design and operational practices of today's space industry. The lower branch of the decision tree represents the available options if the customer initially decides to design a serviceable satellite. This branch represents the alternate satellite design method that allows an operator access to the satellite. The objective of the analysis is to determine under what circumstances the lower branch (serviceable satellite) of the decision tree provides greater value over the upper branch (non-serviceable satellite). Under these circumstances, a serviceable satellite design will provide a customer with more value than a traditional satellite design. Thus the satellite access problem is resolved and support is given for a new paradigm shift in satellite design.

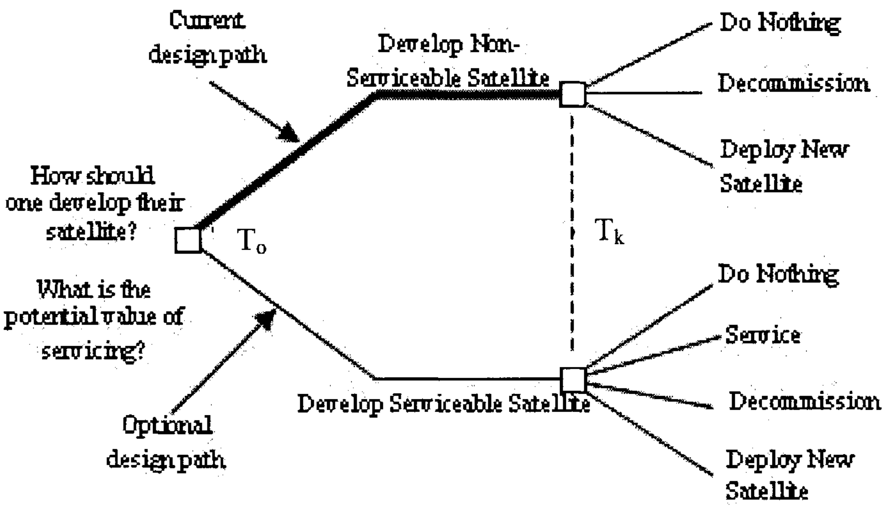


Figure 2–3. Customer Two-Part Decision Process

2.4.1.2. One-Part Decision Process

There are also servicing architectures that can provide additional value for satellites that were not originally designed for servicing. With these architectures, the operator's decision process concerning OOS reduces to a single decision, i.e. the decision to service or pursue other options. Figure 2–4 shows a pictorial representation of a customer's one-part decision process. In this decision, the value prior to the decision to service is irrelevant. Determining whether a satellite operator will choose to service reduces to determining whether the servicing branch of the one-part decision process provides greater value after the time of servicing than the remaining branches.

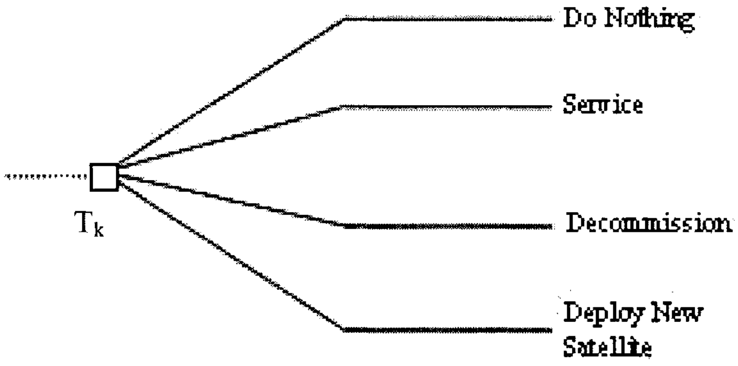


Figure 2–4: Customer One-Part Decision Process

2.5. Conclusions

To determine if OOS is feasible, one must be able to determine if an OOS market exists. To determine if an OOS market exists, both the customer's maximum servicing price and the provider's minimum servicing price must be determined. By adopting the customer-centric approach suggested by Saleh, the customer's maximum servicing price can be determined independent from the servicing architecture. This separation of customer and provider allows an evaluation of servicing from two different perspectives: one in terms of the functions of servicing and the other in terms of the forms of servicing. The functions of servicing are customer driven while the forms of servicing are provider driven.

To determine if servicing is feasible, one must understand the value that servicing offers the customer. The customer's need for servicing can be broken into four fundamental functions. These functions of servicing are asset assessment, asset re-organization, asset restoration, and asset augmentation. The evaluation of the value delivered by servicing will differ based on which function of servicing fulfills the customer's need. For instance, asset restoration and augmentation require that a satellite be designed for servicing. Due to the need for a serviceable design, the evaluation process takes on a two-part decision process: the decision to design for servicing and the decision to service. If the function of servicing does not require a serviceable design, the evaluation process reduces to a one-part decision process, the decision to service.

By examining the customer's decision process, one can determine the servicing price at which the customer is indifferent to servicing versus alternative forms of generating value. The servicing price at which this occurs is the customer's maximum servicing price. Consequently, the value of servicing for the point at which the customer is indifferent to servicing versus any alternative form of generating value is zero. By following the customer's decision process for a given functional need, the point at which the value of servicing is zero can be found, and the customer's maximum servicing price can be determined.

The next chapter will discuss the process for determining the value of OOS suggested by Saleh and later implemented by Lamassoure and Joppin. Chapter 3 discusses how customer value is computed from the future uncertainty in the satellite's future. Based on this uncertainty, the customer's maximum servicing price is determined by finding the point at which the value of servicing is zero.

Chapter 3. Determining the Value OOS Delivers to the Customer

To determine if OOS is feasible, one must be able to predict the additional value that servicing can offer. If servicing provides no additional value above that provided by the current operation and development of satellites, then what value does it have? The problem with determining the additional value provided by OOS is that the value of OOS is rooted in uncertainty. For instance, the augmentation of a satellite with new technology depends on the development of new technology, which is uncertain. Restoration of a satellite depends on when a satellite develops a failure, which is unknown. In fact, if the future were not uncertain, servicing would not provide any additional value. If the future were certain, a satellite designer would design for these future certainties and thus have no need to access the satellite in the future; i.e. thus no need for OOS. Unfortunately, there is no crystal ball to predict the future and thus servicing has the ability to provide a satellite operator with additional value.

The slow adoption of OOS by the satellite industry is due to the industry's impression of uncertainty. However, it should be noted that the one exception to the slow adoption of OOS can be found in the US Department of Defense (DoD). Currently, the DoD is looking into OOS as a possible way to provide satellite upgrade and refueling capabilities (See Orbital Express program in Chapter 1). In general, the opinion held by the satellite industry is that designing for uncertainty is a negative design attribute. As previously discussed, the industry appears to prefer to take a very risk-adverse position when it comes to space applications. Because the value provided by OOS is uncertain, the industry may not be quick to adopt a system dependent on uncertainty.

The Iridium constellation is one example of a satellite program that was unable to react to uncertainty, resulting in a large negative response. In the case of Iridium, the uncertainty about the number of users had a dramatic effect on the success of the network. It turned out that the number of users was overestimated due to the unexpected adoption of terrestrial-based cellular phones. As a result of the overestimate of users, Iridium was forced to charge a high per minute fee to compensate for the loss. The convenience of a global cell-phone never justified this high cost and as a result the Iridium customer base never increased; eventually Iridium filed for bankruptcy.

It appears that one of the major obstacles to the development of OOS may be the negative connotation the satellite industry has associated with uncertainty. At the moment, the only way to change this attitude may be to quantify the additional value that OOS offers over conventional satellite design.

3.1. Deriving Value Out of Uncertainty

The determination of the customer's additional value provided by OOS begins with examining the uncertainty in a satellite's future. For any customer, uncertainty about the future has some effect on customer value. However, uncertainty in the future is not necessarily negative. Future uncertainty also provides the potential for positive change. Saleh et al. emphasize that it is important to understand that "uncertainty is not a synonym for risk any more; it can even become a source of value (Saleh et al., 2003)." With any type of uncertainty, there are always two sides to the coin, an upside and a downside. It is by exploiting the upsides of uncertainty that OOS has the ability to generate additional value over traditional designs that cannot distinguish between the upside and downside of uncertainty.

Traditionally uncertainty has held a negative connotation in the satellite industry; but the idea of uncertainty generating positive outcomes is common among other industries. For instance, in the case of the stock market, the future price of a stock is uncertain. If the price of a stock goes up, greater profits will be created for the owner of that stock. However, the owner of the stock understands and accepts a given level of risk associated with the potential for the stock price to fall. In the stock market, the only thing that is certain is that the price of a stock will change; it will either go up or down. What is uncertain is the magnitude and direction of the change.

Similar to the price of a stock, the value generated by a customer's satellite can either go up or down according to the change in the satellite's underlying market. If the satellite's underlying market goes up, the satellite will deliver more value to its operator, if the market goes down the satellite will lose value. The underlying market for satellites is the reason a satellite is launched in the first place. For instance, the underlying market for a communications satellite is the current communications market. Satellite operators meet the demand of the communications market by launching a commercial satellite in order to provide communications capabilities over a given service region. The price that consumers pay for this service is the driving force behind the customer's value.

The uncertain satellite market drives the future price that a satellite operator can charge. If the price that a satellite operator can charge for communication capabilities goes up, the satellite will generate more value for the operator. If the price of the communication capabilities goes down, the satellite will lose value. The goal of the satellite operator is to take advantage of the upside of the uncertainty and protect against the downside. By understanding how uncertainty in the underlying market affects value, one can determine the additional value produced by the flexibility to react to this uncertainty.

On Wall Street, a very similar practice of protecting against/limiting losses and capturing gains exists. In fact, Wall Street has economic mechanisms that allow for this exact outcome. Certain purchase mechanisms allows for an investor to make a future decision concerning whether or not to buy an investment. The future decision allows the investor to react to uncertainty in the market by purchasing an investment if the market is up or do nothing if the market is down. Economics typically refer to the mechanism in which investors can make future decisions with regards to buying or selling of an investment as an option.

3.1.1. Options

An option is the right, but not the obligation, to pursue an event. Options commonly occur in the area of stocks and commodities. In the stock market, a consumer can purchase a European call option on the stock that gives the consumer the right to purchase a stock at the end of a certain exercise period at a given price, known as the strike price. In return for the ability to purchase the option the consumer must initially pay some small fee (Wall Street Journal, 1999). Options generate value because the investor is given the right to choose whether or not to exercise the option. If by the end of the exercise period the current price of the stock (S) was above the strike price (K), the consumer would exercise the option and have a positive payout (S-K). However, if the stock price were to fall below the exercise price of the stock (K>S), the consumer would not exercise the option. The payout of the option would then be zero, not K-S, and the consumer would only loose the initial fee paid to purchase the option. What makes options unique is the asymmetric payout that results from the investor's choice about exercising the option. Modeling the uncertainty in the payout generated by options is simply a function of knowing the strike price of the option and then predicting the future price of the stock.

3.1.2. OOS as an Option

OOS can be thought of as an option on the future value of a satellite. OOS allows a satellite operator to capture additional value brought about by future uncertainty, similar to how stock options allow investors to generate profits. In terms of OOS, the additional cost that is incurred to design a serviceable satellite can be viewed as the initial price one pays to purchase a servicing option. By designing a serviceable satellite, the satellite operator is given the right, but not the obligation, to service the satellite at some future point in time. The satellite operator will only exercise the servicing option if the outcome will be more valuable than not servicing.

Similar to stock options, if the operator chooses not to service, the operator will be left with the same value (additional value = zero) and will have only incurred the additional cost associated with designing a serviceable satellite. OOS thereby mimics the asymmetric returns that are typical of a stock option by granting a satellite operator the flexibility to gain additional value through servicing while allowing the operator the ability to prevent a significant loss. The value of OOS, or payout, is similar to that of a stock-option. With a few small assumptions, the value of OOS can be determined in the same way that the value of a stock option is determined.

3.2. Modeling Future Market Uncertainty

How can the value of servicing be determined? The Nobel Prize winner Robert Merton stated that "the future is uncertain … and in an uncertain environment, having the flexibility to decide what to do after some of that uncertainty is resolved definitely has value. Option-pricing theory provides the means for assessing that value (Merton, 1997)." Option pricing theory is commonly known as Black-Scholes theory. Black-Scholes theory originated from the Black-Scholes equations developed by Fisher Black and Myron Scholes in 1973 (Black and Scholes, 1973). The Black-Scholes equations can be used to model the varying price of future investments over time.

One of the key assumptions of the Black-Scholes equations is that the varying price of the investment over time follows Brownian motion. Brownian motion is commonly known as the random movement of a tiny particle suspended in a fluid or gas. In the case of stock prices, Brownian motion is used to model the random change in stock prices over time. In this thesis, Brownian motion will be used to model the uncertainty in the changes in the satellite's underlying market over time.

Saleh was the first to use option pricing theory, commonly known as real options analysis when pertaining to engineering systems, as a method with which to determine the value provided by OOS (Saleh, 2002). Saleh modeled the satellite's future uncertainty, under the assumption of Brownian motion, as a random change in the satellite's market. Saleh modeled OOS as a servicing option provided to the satellite operator. Using this model, he was able to determine that additional value of OOS. For a more detailed discussion of real options theory, the reader is referred to Trigeorgis (Trigeorgis, 1996). The next section describes Saleh's real options approach and the evaluation method laid out by Lamassoure (Lamassoure, 2001) and Joppin (Joppin, 2004) for determining the value of OOS.

3.2.1. Geometric Brownian Motion

The core concept in Saleh, Lamassoure, and Joppin's work is the idea of flexibility and generating value by reacting to future uncertainty. The first step is to determine what uncertainty exists in the underlying market and how it affects customer value. Typically one or more uncertain market parameters exist that provide the customer with value. A typical assumption used by real options theory is that the change in the uncertainty follows Geometric Brownian motion. The effect of modeling the change in the market with Geometric Brownian motion is that the range of the potential market values is bounded between zero and infinity. Thus the benefit of modeling the market uncertainty with Geometric Brownian motion is that the uncertainty more precisely models the trends of a commercial market. Geometric Brownian motion of the uncertainty can be simplified to Brownian motion of the logarithm of the uncertain market (Joppin, 2004).

The uncertainty in the market, x, can be examined in terms of the change in the market over time; i.e. the ratio between the predicted market value per unit time, $X_{th}(t)$, and the current value, X(t). "Using the Ito Lemma equation it can be shown that if x follows a Geometric Brownian Motion with drift α and volatility σ, Y defined as Y = ln(x) follows a Brownian Motion with drift $(\alpha-\frac{1}{2}\sigma^2)$ and volatility σ. Therefore the change in the logarithm of x is normally distributed with mean $(\alpha-\frac{1}{2}\sigma^2)t$ and variance $\sigma^2 t$ (Joppin ,2004)." By knowing the current market value at a given point in time, X(t), the change in the market uncertainty is log-normally distributed with an expected rate per unit time of $e^{\alpha t}$ and rate of variance per unit time of $\alpha\sqrt{t}$. For example, the change in the selling price for satellite bandwidth over time is uncertain and has a direct effect on customer value. The only information required to predict the future selling price of bandwidth is the current selling price of the bandwidth, X(t), and the volatility (σ), and drift (α) of the change in the selling price. Equation 3-1 provides a description of the relative change in the uncertainty parameter and Equation 3-2 describes the associated probability distribution with respect to time.

Equation 3-1

$$Y = \ln(x), \quad x = \frac{X_{th}(t)}{X(t)} = \frac{X(t+\Delta t)}{X(t)}$$

Equation 3-2

$$p_{\Delta t}(x) = \frac{\exp\left\{-\frac{\left[\ln(x) - (\alpha - \sigma^2/2)\Delta t\right]^2}{2\sigma^2 \Delta t}\right\}}{x\sqrt{2\pi}\sigma\sqrt{\Delta t}}$$

3.2.2. Binomial Tree Distribution

Instead of modeling the uncertainty as a continuous change in the market, it is easier from an analysis point of view to describe the continuous uncertainty as a discrete uncertainty. To move from the continuous domain to the discrete domain, the Geometric Brownian motion of the market uncertainty will be looked at as the continuous limit of a discrete random walk. The random walk of the uncertainty parameter, Y, will be modeled with a binomial tree distribution. The binomial tree distribution is developed such that the range of potential values reproduces the expected drift and volatility of the Geometric Brownian motion, see Figure 3–2.

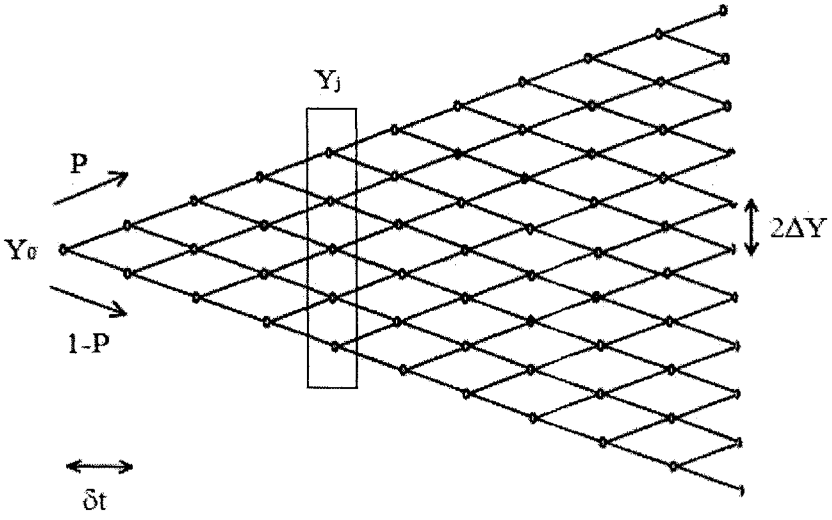


Figure 3–1: Sample Log-Transformed Binomial Tree Distribution (Lamassoure, 2001)

To mimic the Brownian motion behavior, the binomial tree is characterized by a step up of ΔY or a step down of ΔY for each time step. The fixed change in ΔY allows for independence between the value of the market at any point in time and the path (sequence of ups and downs of the market) that was followed to attain that value. Equation 3-3 describes the step size up or down over any time step.

The independence of the market value relative to the path can be seen in Figure 3–1. Notice that the second point in the third column (third time step) could have been attained by either a initial step up in the market followed by a step down, or by an initial step down in the market followed by a step up. Since a given market value at any point in time is path independent, the only remaining unknown in the market prediction is determining the probability of attaining each potential market value.

In addition to capturing the Markov relationship (an element of Brownian motion) of the market uncertainty, the binomial tree was chosen because it allows for simple calculation of the probabilities associated with future market values. The values of the market described by the binomial tree must satisfy the probability distribution described in Equation 3-2. To satisfy this equation, each point in the binomial tree is given a probability p of an upwards step, and probability 1-p of a downwards step at any point in time. The probability of an upwards step, p, is described by Equation 3-4.

Equation 3-3

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

Equation 3-4

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

The size of each discrete time step is determined by the length of the evaluation time period divided by the desired number of time steps, L. It is common for the length of each time step in the binomial tree (δt) to correspond to the units of the drift (α) and volatility (σ) of the underlying uncertainty. By matching the time periods for the market volatility and drift with the time period for the discrete time step of the binomial tree, additional model uncertainties are avoided. In practice, the market volatility and drift are determined from historic market data over a given period of time. A problem that frequently occurs in modeling future uncertainty is that historic market data can be spaced over a long time period (years), but the operator wishes to map the market on a small time scale (months). If this were the case, the operator will have to accept additional uncertainty in the model due to the interpolation that would be required to change between time scales. In order to avoid this form of added uncertainty, all case studies in the thesis will assume that the discrete time steps of the binomial tree correspond to the units of time for the historic market volatility and drift.

The possible values for the change in the market are described by the range of values in the binomial tree. The potential uncertainty values can be described at any point in time T_j, where $T_j = T_o + j\delta T$ and $j=0 \rightarrow L$. The range of the logarithm of the change in the uncertainty, Y, at any time, T_j, is donated as $Y_{i,Tj}$ where $i = 1 \rightarrow n$. This range of Y values at any point in time is given by Equation 3-5. Because the change in uncertainty is modeled as Geometric Brownian motion, $Y_{i,Tj} = \ln(X_{i,Tj}/X_o)$. Rearranging, the future value of the uncertainty parameter can be described by $X_{i,Tj} = X_o * e^{(Yi,Tj)}$ The corresponding probability of obtaining X_i at T_j is given by Equation 3-6.

Equation 3-5

$$X_{T_j} = \begin{cases} X_o * e^{\wedge} \begin{bmatrix} Y_o + 2Y\left(\frac{J-1}{2}\right) \\ \vdots \\ Y_o \\ \vdots \\ Y_o - 2Y\left(\frac{J-1}{2}\right) \end{bmatrix} & \text{for} \quad J = 1,3,5,7,.... \\ X_o * e^{\wedge} \begin{bmatrix} Y_o + Y\left(\frac{J-2}{2}\right) \\ \vdots \\ Y_o + Y \\ Y_o - Y \\ \vdots \\ Y_o - Y\left(\frac{J-2}{2}\right) \end{bmatrix} & \text{for} \quad J = 2,4,6,8,.... \end{cases}$$

Equation 3-6 (H.S.Ang and Tang, 1975)

$$P(X_{i,T_j}) = \left(\frac{(j-k)!}{(i-l)!(j-k-(i-l))!}\right) p^{j-k-(i-l)}(1-p)^{(i-l)}$$
$$\text{where} \quad k=1, l=1$$

3.3. Calculating Customer Value

The use of options theory proposed by Saleh (Saleh, 2002) laid the ground work for the evaluation methods described by Lamassoure (2001) and Joppin (2004). Lamassoure's and Joppin's evaluation methods consist of a reverse valuation method to determine the value of servicing. Lamassoure and Joppin assume that the operator will seek what is referred to as the "optimal strategy." The optimal strategy is the series of choices that will lead a decision maker to the greatest overall lifetime value. To determine the optimal strategy, Lamassoure and Joppin map the binomial tree distribution used to describe the market uncertainty to the satellite operators decision tree with regard to servicing, see Figure 3–2. This mapping of uncertainty to the decision process allows prediction of the value of the market at the point where the operator decides on servicing.

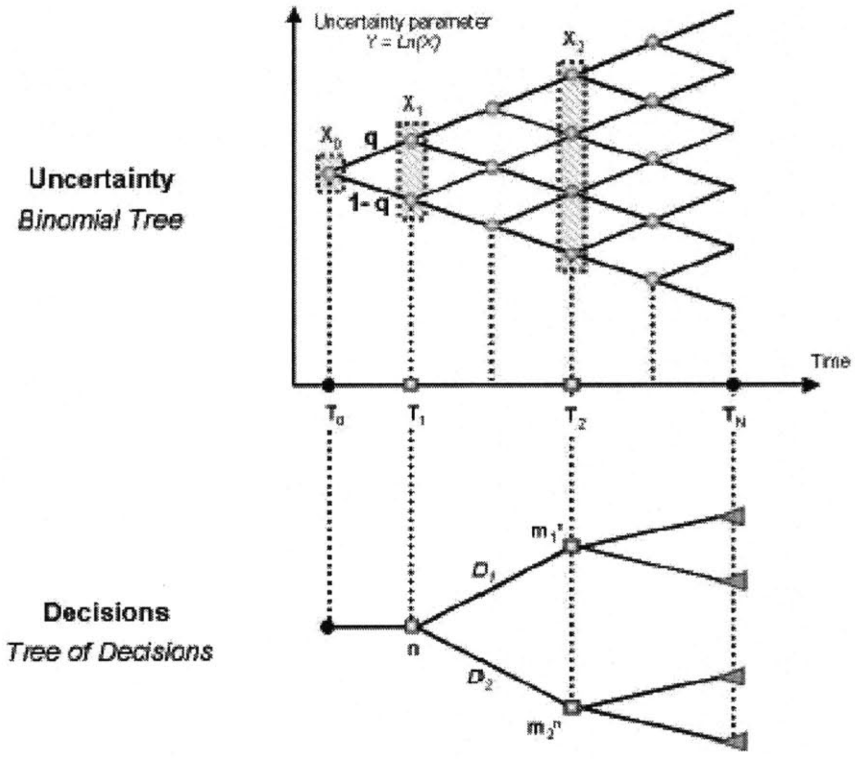


Figure 3–2: Conceptual Relationship Between Binomial Tree and Possible Decision Tree (Joppin, 2004)

Because the operator is given the choice to service, but not the obligation, the satellite operator is able to decide which path will generate the greatest value for each value of the market uncertainty. Thus, to achieve the optimal strategy, the satellite operator makes different decisions for different values of the market such that the greatest value is delivered. The operator's optimal strategy is thus the decision that would be made when faced with each potential value of the market at any point in time. This strategy mimics the asymmetric results that are delivered by options. Under the strategy, if servicing provides the greatest value for a given market value, the operator will choose to service, otherwise the operator will pursue another course of action.

Before describing the process, several decision elements used to determine customer value are discussed below. The majority of the design elements have been gathered from previous work focusing on the value of OOS and a few have been added to reflect current thinking.

3.3.1. Valuation Analysis Elements

3.3.1.1. Baseline Strategy

The baseline strategy is the reference strategy to which all options are compared. In this thesis, the way in which satellites are typically built and operated in today's satellite market is the baseline strategy. The baseline strategy consists of an initial satellite that was not designed to be serviced. The satellite will remain operational for its entire expected operational lifetime. When given the chance to make decisions concerning a satellite's future, the satellite operator will always choose to do nothing. If a replacement satellite is launched at the end of the initial satellite's operational life, this satellite will also be designed without the ability to be serviced. The value of the baseline strategy is a function of the initial expected benefit of the satellite over its lifetime along with all expected deployment and operational costs.

3.3.1.2. Uncertain Parameter(s): X

The basis for generating value through OOS is the premise of uncertainty. In any evaluation of OOS, there is the potential for a number of uncertainties. The uncertainty in the satellite's market is the basis for the satellite's additional value; this uncertainty was already discussed in the previous section. It is assumed that any other uncertainties are independent of the market uncertainty. Typical additional uncertainties may deal with the servicing of the satellite, the design of the satellite, or any other customer developed uncertainty. A few potential uncertainties that can effect the decision to service are: readiness of new technology, readiness of new satellite design, uncertainty in launch, and satellite lifetime failures. No matter the form of the uncertainty, all uncertainties will be modeled as a range of potential values with an appropriate probability distribution. If M uncertainties exist in a single model, the uncertainties, $(X_i)_M$, are described as a vector $[X_1, \ldots X_M]$.

3.3.1.3. Time Horizon -T_H

The time horizon is defined as the period of time from the customer's initial decision, or launch, to some distant point in the future. The purpose of choosing a distant point in the future is so that the cumulative discounted cost and benefit of a customer's decision can be compared over the same time period. In the past, this period of time has been chosen to be the same as the expected lifetime of the satellite. However, it will be shown later that the time horizon should be extended beyond a single satellite lifetime. In this thesis, the time range defined by the binomial tree distribution is equal to the time horizon of the evaluation (i.e. $T_L=T_H$).

3.3.1.4. Decision Point(s) - T_k

Decision points represent a point during the operational life of the satellite, T_k, where the customer has the ability to make a decision concerning the future operation of the satellite. In the case of OOS, the decision point generally represents the point in time at which the customer has the option to service the satellite or pursue a more beneficial option. Throughout the operational life of a satellite, the customer may have the option to make multiple decisions. Multiple decision points will be described as an array of decision points and represented by $T_{k,n}$, where $T_{k,n} = T_{k,0} + n\delta T_k$ and δT_k represents the change in time between decisions. Due to the discrete nature of the market uncertainty, all decision points in the evaluation will occur at some point in time described by the binomial tree distribution. Again, Figure 3–2 should provide some clarification.

3.3.1.5. States of Operation – S

The very nature of a flexible system is to design a system such that it can react to future uncertainty. One method for providing flexibility is through the system's ability to change its operational state in reaction to uncertainty. Let S donate an array of the possible operational states of the system at all points in time. Examples of operational states of the system can be: normal operation, replacement satellite, serviced satellite, or removal from the market. A satellite operator changes the operational state of the satellite by switching to that state by way of a previous operational state. Initially the first operational state of the satellite would represent normal operation. For any decision point let S_i, represent the entry states of the system, i.e. the state of the system before the decision point. Next let S_f represent the exit states of the system, or the state of the system after decision point. The discrete nature of the uncertainty constrains the evaluation and forces the assumption that the system can only change its operational state at a decision point.

3.3.1.6. Underlying Market

The underlying market is the market which the target satellite serves and consequently generates benefit for the operator. It is assumed that the uncertainty in the market is independent of the operator's future decisions. The underlying market is represented in similar fashion to any other uncertainty parameter. Examples of an underlying market can be the uncertainty around the price of a gigabit per second of data rate, the location of a major theatre of war, or the location of inclement weather, etc. It is the uncertainty in this market that allows OOS to generate benefit for the customer. The range of potential market values described by the binomial tree distribution at time T_j is denoted as $X_{i,Tj}$, where $T_j=t_o+j\delta t$.

3.3.1.7. Benefit Function-EB

A customer's benefit function describes the benefit a customer gains over the satellite's operational lifetime. The choice of the benefit function should be one such that it describes the importance for the satellite operator. Ideally a satellite operator's benefit function should be independent of the satellite's design. For instance, a customer seeks to generate revenues, but revenues do not define the design of the satellite. Benefit is strictly some function of the underlying market and not a function of the costs of operating the satellite; i.e. the benefits for a commercial satellite operator are the revenues that the satellite generates, not the revenues minus the cost. In the case of a discrete step analysis, a customer's benefit is constant and aggregated over each time step $[T_{n-1};T_n]$.

3.3.1.8. Risk

The most significant and most misunderstood parameter in the development of OOS is risk. In the market of OOS several risk drivers exist. Operators take on the risk that a satellite will not reach orbit due to a launch vehicle failure. Once in orbit, a satellite is exposed to the risk of an upper stage failure, which prevents a target satellite from reaching its target orbit. In the case of servicing, there is the risk that a servicing will cause harm to a satellite or even worse destroy the satellite. Servicing also introduces a new risk associated with the potential of third party effects (orbital debris caused by servicing that affects a third party's satellite). Third party effects create possible liability concerns for the satellite provider and satellite operator in the case where a third parties satellite was damaged as a result of servicing.

Each type of risk has its place in the evaluation of OOS. With respect to servicing, the customer is mainly concerned with the risk of servicer failure. For the purpose of this discussion, the risk associated with servicing failure will be noted as $\Re_{SVR.}$ While third party effects are a concern, these effects are more than likely to be a concern for the service provider and not the satellite operator. Chapter 8 provides a more detailed discussion of the potential liability concerns over third party effects. For now, it is assumed that any insurance required for third –party-effect prevention will be accounted for in the servicing price. In determining the value that OOS delivers to the customer, risk is simply viewed as a probabilistic reduction in benefit. Equation 3-7 describes the incorporation of risk into the satellite operator's calculation of benefit.

Equation 3-7

$$EB^S(X_i)_M = (1-\Re^S_{SVR})EB^S(X_i)_M + (\Re^S_{SVR})EB^{Failure}(X_i)_M$$

3.3.1.9. Cost

Three forms of cost exist in the evaluation of OOS; 1) the cost of operation, 2) the cost of switching between operational states, and 3) the cost of the initial capital investment. In order to evaluate the different cost structures, all costs will be discounted to same year dollars representing the cost at the time of launch. In converting cost to launch year dollars, a discount rate, $\Re_{DIS,}$ and an interest free rate, $\Re_{IFR,}$ will be used to determine the customer's opportunity costs. The customer's internal rate of return, $\Re_{IRR}$, will then be the sum of the discount rate and the interest free rate.

Due to the discrete nature of the analysis, the operational cost will be evaluated over each time period, $[T_{n-1};T_n]$, for each given operational state of the system. Each operational state of the system has a fixed cost that is required for maintain the satellite in operation. Typically this cost includes the cost of ground station, ground support, operating personal, etc. In this thesis $C^{S}_{op,[T_{n-1};T_n]}$ represents the cost of operating the system in state S.

At each decision point, the customer has the option to switch between operational states of the system to gain additional value. However, a cost is associated with switching between the states of the system. The cost of switching could be the cost of abandonment, the cost of relocation, or the cost of servicing. In the case of OOS, the switching cost would most likely represent the servicing cost. The cost of switching from any initial state, S_i, to a given final state, S_f, is denoted as $C^{S_i \to S_f}$

The last cost element in the evaluation is the initial cost of the satellite. The initial satellite cost included the cost of satellite procurement, the cost of launch, insurance costs, research design test and evaluation (RDT&E) costs, and any other costs associated with the satellite's deployment. The initial operating cost of a given satellite is represented as C_{IOC} .

3.3.1.10. Value Function

The value provided to the customer by operating the system is a function of the customer's benefit of operating the system and the cost of operating the system. Assuming the cost of operation and the cost of switching between operational states of the system are constant regardless of the value of the underlying market, the expected value (*EV)* over period $[T_{n-1};T_n]$ can be denoted according to the following equation:

Equation 3-8

$$EV_{[T_{n-1},T_n]}^{S_i \to S_n}(x)_M = f\left(EB_{[T_{n-1},T_n]}^{S_i \to S_f}(x)_{T_{n-1},M}, EB_{[T_n]}^{S_f}(x)_{T_n,M}, C^{S_i \to S_n}, C_{op\,[T_{n-1},T_n]}^{S_f}(x), C_{IOC}\right)$$

For the case of determining the expected value over the range of uncertain market values, X_i, at any point in time, the expected value is calculated by multiplying the customer's value as a function of the market uncertainty by the probability of attaining that value. The expected value to the customer over period $[T_{n-1};T_n]$ for state S is determined by the following equation:

Equation 3-9

$$EV_{[T_k,T_{k+1}]}^{S^i} = \sum\left[EV_{[T_k,T_{k+1}]}^{S^i \to S^f}(x_{i,T=T_k})_M * p\left(\frac{X_{i,T=T_k}}{X_{T=T_o})}\right)\right]$$

3.3.1.11. Utility Function

A utility function is used to capture the customer's perception of risk and rewards. Ross defines utility as "a dimensionless parameter that reflects the 'perceived value under uncertainty' of an attribute. Often used in economic analysis, utility is the intangible personal goal that each individual strives to increase through the allocation of resources." (Ross, 2003) It is important to note that the definition of utility is not the same at that used by Saleh and Lamassoure. The "utility metric" used by Saleh and Lamassoure, Saleh, et al. 2003, is representational of the benefit function used in this article.

The purpose of the utility function is to capture the relationship between the additional value from servicing and the operator's perceived risk. A decision-maker is classified as exhibiting one of three forms of risk-preference. The three forms are: "risk-adverse', "risk-neutral", and "risk-prone" (DeNeufville, 1990). A "Risk-neutral" decision maker is described as a decision-maker who has no risk-preference because he makes decisions on an expected value basis. A "risk-adverse" decision maker is described as one who tends to prefer more certain outcomes although the outcomes tend to be less profitable. On the contrary, a "Risk-prone" decision maker is described as one who chooses options that on average are less profitable, but have the possibility of significant rewards. Based on the customer's risk preference, a customer's utility function can have either a positive or negative effect on the customer's valuation of the system and therefore can effect the customer's decision to service. The customer's perceived value is determined as a function of the utility function *U* and the expected value, as shown below.

Equation 3-10

$$PerceivedValue = U\left(EV\right)^{S}_{[T_{n-1},T_n]}$$

3.4. Real Options Analysis

The purpose of real options analysis is to determine the additional value that results from reacting to future uncertainty. The overall purpose of the options analysis is to determine the customer's optimal servicing strategy. Recall that the optimal strategy is the decision that a satellite operator makes, into order to maximize value, when faced with a given market value. The satellite operator's optimal choice is the one that maximizes future benefit over the lifetime of the system.

The satellite operator's decision process represents a Markov process because only the future value of the satellite matters in the operator's decision. The earlier decision points in time do not affect the current decision because the optimal strategy assumption assumes that a decision maker will have chosen an optimal strategy up until the current point. By modeling the customer's decision process as a Markov process, the customer's optimal operation strategy is determined through a reverse evaluation method. For a more detailed discussion, the reader should refer to (Joppin, 2004). A brief description of the real options evaluation process is provided below.

3.4.1. The Evaluation Process

To determine the customer's expected value over the entire time horizon, the evaluation process is broken into two segments: 1) the expected value from deployment to the first decision point ($T_{k,1}$) and 2) the expected value from the first decision point to the time horizon (T_H). Since the second segment can contain multiple decision points, there is a need to determine the optimal strategy for the customer at each decision point.

The overall optimal strategy for all decision points are the decisions that maximize the customer's value over the decision period, $[T_k,T_H]$. The bellman equation states that the expected value over any period of time $[T_k, T_H]$ can be broken down into multiple parts; $[T_k,T_{k+1}]$, … $[T_{k,n-1},T_{k,n}]$,$[T_{k,n},T_H]$. Thus the customer's optimal strategy is determined by working backwards and calculating the expected value over the decision period $[T_{K,},T_H]$ for each decision period $[T_{k,n-1},T_{k,n}]$. Starting at the time horizon, T_H, at each decision period $[T_{k,n-2},T_{k,n-1}]$ one must calculate the expected benefit, cost, and value for the future decision points, $[T_{k,n-1},T_{k,n}]$, making sure to take into account the optimal strategy computed at the future decision point.. This process is repeated until one reaches the first decision point (T_k).

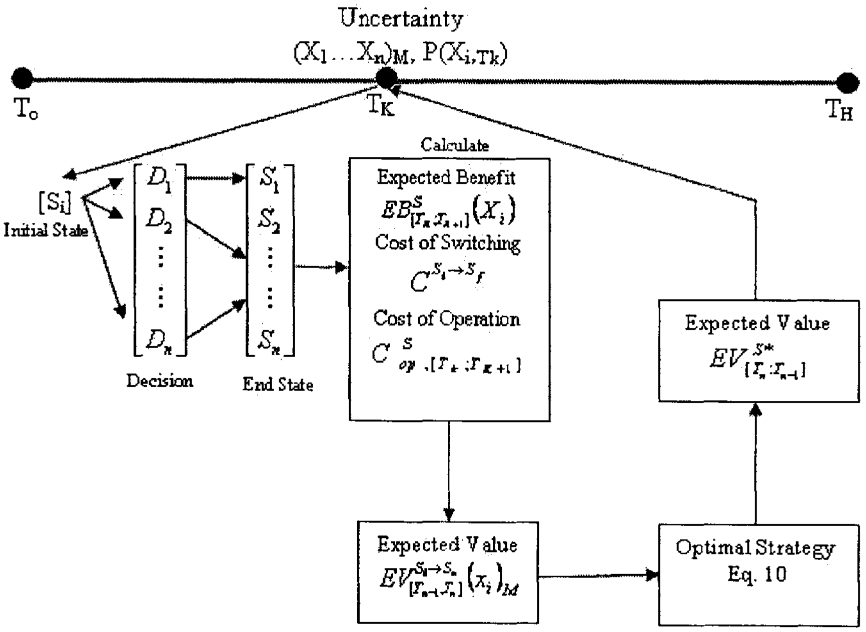


Figure 3–3: Conceptual Valuation Process [1]

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[1] Adapted from Carole Joppin. *On-Orbit Servicing for Satellite Upgrades*. Master's Thesis. Massachusetts Institute of Technology. February 2004. pg 98.

At any given point in time, the optimal strategy depends on the current state of the customer's underlying market $(X_{T_k})_M$ and their perception of the expected value. Equation 3-11 shows the decision model for determining the customer's optimal strategy at T_k given $X(T_k)_M$. A conceptual model of this process is adopted from Joppin's work and can be found in Figure 3–3.

Equation 3-11

$$\begin{array}{cc} & \xrightarrow{\text{Possible States of the System}} \\ \begin{array}{c}\text{Range of Market}\\ \text{Uncertainty}\end{array}\Big\downarrow & \begin{bmatrix} U\left[EV_{[T_n:T_{n-1}]}^{S_1 \to S_1}(X_1)\right] & \cdots & U\left[EV_{[T_n:T_{n-1}]}^{S_1 \to S_n}(X_1)\right] \\ \vdots & \ddots & \vdots \\ U\left[EV_{[T_n:T_{n-1}]}^{S_1 \to S_1}(X_n)\right] & \cdots & U\left[EV_{[T_n:T_{n-1}]}^{S_1 \to S_n}(X_1)\right] \end{bmatrix} \end{array} = \begin{bmatrix} U\left[EV_{[T_n:T_{n-1}]}^{S_1 \to S^*}(X_1)\right] \\ \vdots \\ U\left[EV_{[T_n:T_{n-1}]}^{S_1 \to S^*}(X_n)\right] \end{bmatrix} = EV_{[T_n:T_{n-1}]}^{S_1 \to S^*}$$

Where:

$$EV_{[T_{n-1},T_n]}^{S_1 \to S_n} = EV_{[T_{n-1},T_n]}^{S_1}(X_i)_{T_{n-1}} + e^{-\Re_{IRR}(T_n - T_{n-1})}\left[p\left(EV_{[T_n]}^{S_{n1}}(X_{i+1})_{T_n}\right) + (1-p)\left(EV_{[T_n]}^{S_{n1}}(X_{i-1})_{T_n}\right)\right]$$

The state of the satellite, S_i, represents the initial state of the satellite at the decision point. S^* represents the optimal end state at T_k, given the underlying market value. S^* is found by determining the end state that provides the maximum value for given market value. The optimal end state, S^*, is therefore computed by finding the maximum value among all the columns in Equation 3-11 for a given row. The optimal strategy over period $[T_k, T_{k+1}]$ is denoted as $EV_{[T_n:T_{n-1}]}^{S_1 \to S^*}$, which is equivalent to Joppin's denotation of $I^{n \to m}$ for the optimal strategy. The expected value of state S_i over period $[T_K, T_{K+1}]$, $EV_{[T_k,T_{k+1}]}^{S_i}$,no longer depends on the end state of the system, but only on the initial state.

This process is then repeated for all prior decision points. By repeating the process one obtains with the optimal strategy over the period $[T_k, T_H]$. The total value is then the discounted sum of the customers optimal strategy after the decision point, $[T_k, T_H]$, and the value generated up until the decision point, $[T_o, T_k]$.

Equation 3-12

$$EV_{[T_0,T_H]} = EV_{[T_o,T_k]} + e^{-\Re_{IRR}(T_k-T_o)} EV_{[T_k,T_H]}$$

3.4.2. Improvements to Suggested Framework

To apply Saleh's customer-centric model and the methodology suggested by Lamassoure and Joppin requires an understanding of the full extent of the customer's decision model. Lamassoure's and Joppin's work focused on determining the value provided by servicing over the design life of a single satellite. Despite the increased accuracy of this work over traditional evaluation methods, it has one major weakness. The previous work examined the value provided by servicing over the lifetime of a single satellite. In doing so, that analysis fails to capture the full value that servicing provides over alternative options.

Recall that in Chapter 2, the satellite operator has either a one-part or two-part decision process based on the form of servicing. In the two-part decision model, the operator has the option to replace the satellite in the upper branch of the decision tree (non-serviceable satellite), the same as they do in the lower branch. Just because servicing may prove to be the best option in the lower branch does not mean that it is the best option overall. By focusing on a single satellite lifetime, Lamassoure and Joppin's research fails to account for the alternative design options that are created by not designing a serviceable satellite. As a result, the failure to capture the more valuable decision leads to inaccurate prediction of the customer's maximum servicing price.

In addition to not fully representing the operator's decision process, both Joppin and Lamassoure fail to capture the full extent of the value created by the customer's decision. In an example of a satellite upgrade, Joppin assumes that the design of a replacement satellite is available at the same point in time that servicing can be provided.[2] The conceptual notion behind on-orbit upgrade is that OOS can provide the customer with additional benefit by introducing new technology earlier than could have otherwise been accomplished. However, the customer has additional means of generating value and is

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[2] Note that Joppin delays the launch of a replacement satellite by two years in order to account for the time of development. Thus the launch of any replacement satellite occurs two years after the decision to replace.

not confined to only the decision points where servicing is possible. Recall that the customer has the option to launch a replacement satellite. It is certainly possible that a satellite is capable of supporting additional value generating units before any new technology was developed. This choice would be the choice of satellite replacement that is represented in the upper branch of the two-part decision tree in Figure 2–3, but the option for replacement would occur at a different point in time. Joppin fails to accurately take the difference in decision points into account and therefore determines the customer's optimal strategy by only looking at the option for replacement at the same decision point as the servicing option. By only looking at decision points where a customer will decide on servicing, Joppin fails to account for the potentially more valuable scenario of early, or later, satellite replacement.

Along the same lines as the previous concern, Lamassoure and Joppin did not account for the option of asset augmentation by a unit-value and unit increase. In the development of a replacement satellite, the satellite operator is not confined to using outdated technology. The development of new technology allows the customer to incorporate new technology into any replacement satellite along with the increase in the number of value-generating units onboard the satellite. The result of incorporating both new technology and more value-generating units on a replacement satellite would be a more valuable satellite that incorporates the benefits of both a unit-value and unit increase. By incorporating both technologies together, the customer has the potential to generate substantially more value than could have been achieved through servicing alone; at best servicing can only provide a unit-value increase. Therefore by not examining this option, Lamassoure and Joppin misrepresented the value that OOS provides to the customer.

Since these potentially more valuable options can occur at different decisions points, there is a need to evaluate the value of all the customer's options on the same time scale. By focusing on the lifetime of a single satellite, the customer's options are not aligned, which results in differing time scales on which to evaluate customer value. By extending the time horizon to cover the lifetime of the initial satellite and its planned replacement the difference in the discounted lifetime value becomes insignificant. Extending the time scale allows for more valuable future options to be compared on the same time scale as less valuable near-term options. The result is a more accurate optimal customer strategy that results in a more accurate prediction of the customer's maximum servicing price.

3.4.3. Determining the Maximum Servicing Price

The objective of the real options approach analysis is to determine the servicing price at which OOS provides greater value than alternative decision paths. The maximum price that a customer would be willing to spend on servicing represents the price at which a customer is indifferent to servicing versus the next most beneficial option. The maximum price at which servicing no longer provides greater value than alternative options can be determined by varying the price of servicing. This price is the point at which the additional value provided by OOS is zero. By determining the maximum servicing price that a customer would spend, an upper limit is placed on the price that a service provider could charge for servicing.

3.5. Case Studies

The next three chapters determine the customer's maximum servicing price for three servicing scenarios. The first example is an asset restoration scenario where a provider extends the operational life of a GEO communications satellite. The purpose of extending the operational life of the satellite is to restore or maintain the value that the satellite delivers to the customer. In a restoration case, the servicer does not increase the value that the satellite delivers to the customer, but simply restores the value to a previous state. The second and third examples are asset augmentation scenarios. The second example focuses on GEO communications satellites, but examines the value that is delivered to a commercial customer through technology upgrades. The third example addresses technology upgrades for the case of a non-commercial customer. This example looks at the upgrade of the Geostationary Operational Environmental Satellites (GOES) weather satellites and determines the value that can be delivered through two potential upgrades.

The first example uses the one-part decision tree and examines a case where a satellite operator only decides whether or not to service their satellite. In this decision model, the servicing option does not require that the target satellite be designed for servicing. The customer has a single decision to make-- whether to service the satellite, replace the satellite, do nothing, or decommission the satellite. The customer will base this decision on the branch of the decision tree that provides the greatest value. Since the value before the decision point is unchanged, a customer is not concerned with the value that is delivered before the decision point. The customer is only concerned with the value beyond the decision point.

The example focuses on the additional value that can result from life extension. In the case of life extension, the option to decommission a satellite would not provide additional value, but the option to service the satellite has the potential to provide additional value. Although the satellite operator also has the option to replace the satellite, which could provide greater value; the replacement option is not considered in this study. If life extension provides positive value to the customer, a feasible market for the life extension of GEO communications satellites exists. The maximum price that a satellite operator would be willing to pay for life extension is determined as the servicing price at which a customer is indifferent to life extension versus decommissioning.

The next two examples examine cases where a service provider augments a customer's satellite either by upgrading the satellite with new technology (unit-value increase) or by the addition of value generating payloads (unit increase).[3] Unlike the life extension case, the upgrade cases require that a satellite be designed for servicing. As a result, the customer's value is determined by focusing on the decision tree represented in Figure 2–3.[4] The decision tree maps the customer's two-part decision analysis concerning their choice to design for servicing or not and potential future decisions in reaction to future uncertainty.

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[3] Make note of part one for a precise definition of unit-value and unit increase

[4] In both augmentation cases, it was assumed that a satellite operator would not be given the choice to decommission the satellite due to the fear of losing their entire market user base.

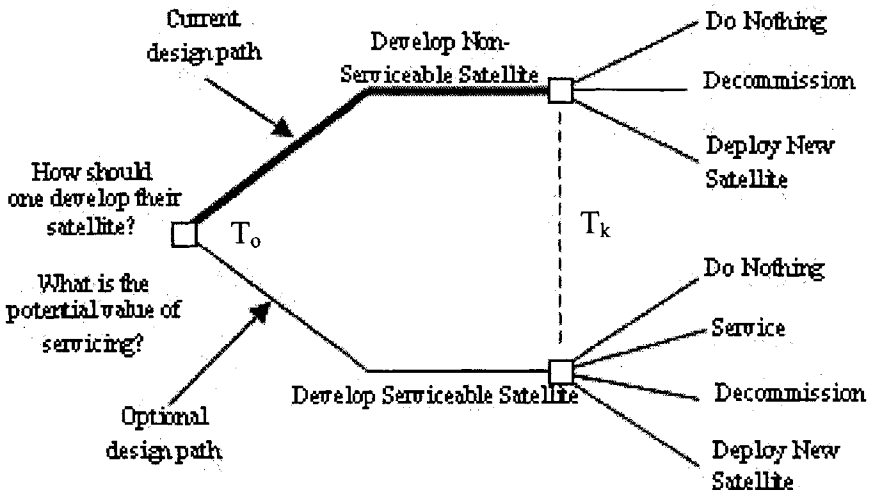

Figure 3–4: Satellite Design Decision Tree

Since a customer's future decisions can only be finalized in the future when uncertainty has been resolved, the purpose of the decision analysis is to determine how a customer should initially design their satellite. By examining the decision tree, when the upper branch of the decision tree provides more value than the lower branch the customer should design their satellite without servicing in mind. However, the customer should design their satellite for servicing if the lower branch provides more value than the upper branch. Therefore, in order to determine how a customer should initially design their satellite one needs to determine the expected value resulting from the decision to design for servicing and the expected value from deciding not to design for servicing.

3.5.1. Additional Uncertainties

The asset augmentation scenario addresses three types of uncertainties. In addition to uncertainty in the underlying market, the future decisions incorporate new technology development uncertainties (potential unit-value increase) and new satellite bus development uncertainties (potential unit increase). An advance in new technology is assumed to increase the capability of each value-generating unit onboard a satellite and as a result to increase customer value. An advance in satellite bus technology is assumed to increase the capacity of the satellite bus and allow a satellite operator to add additional value generating units. It is assumed that any new technology can be applied to any satellite on-orbit (given that is was designed for servicing), but that new bus technology can only be applied to replacement satellites.

In order to capture the effect of a technology development period, a technology freeze of three years beyond the launch date is assumed on all technology. This implies that at a minimum it will take three years to develop any new technology regardless of the satellite operator's action. In reality a satellite operator could always speed up technology development by increasing research and development funding, but this effect was excluded from the analysis. While the technology freeze limits the earliest possible readiness date of any technology, the actual readiness of technology is uncertain. To account for this uncertainty, the readiness of any new technology beyond the technology freeze date, the uncertainty around technology development is assumed to be independent of the decision-makers actions as well as independent of the development of other technologies.

Based on these assumptions, the development of new technology is assumed to follow a Poisson process and can thus be represented by an exponential probability distribution. The exponential probability distribution was chosen because it describes the probability of occurrence of an event as a function of time (H.S.Ang and Tang, 1975). Thus in this case, the exponential probability distribution is used to predict when the development of the new technology will be completed beyond the technology freeze date. Because it is assumed that technology development can occur at any point in time after the first day of any given year, the deployment of any technology developed during a given year cannot be deployed until the beginning of the succeeding year. As a result of the technology freeze, the upgrade or replacement of the target satellite cannot occur until the fourth year of operation. In order to account for a new satellite development period, it is assumed that a decision maker will have to wait two years between the decision to launch a new satellite and the deployment of that satellite.

In addition to the additional value provided by upgrading or replacement, the customer has the unique option to incorporate new technology into the replacement satellite. The incorporation of both technologies results in a replacement satellite that incorporates the benefits of both a unit-value and unit increase. For a customer to launch a more powerful replacement satellite, both the new technology and new bus technology would need to be developed at, or before, the customer's decision for replacement.[5] Therefore, the readiness for new technologies can either work for or against the customer.

3.6. Conclusions

Throughout most of its existence, the aerospace industry has seen uncertainty as a negative aspect of design. This apparent misrepresentation probably results from a misunderstanding of the difference between risk and uncertainty. Risk is a form of uncertainty, but uncertainty is not limited to risk. Uncertainty has an upside and a downside. The downside is known as risk, while the upside can be thought of as rewards. It is the upside of uncertainty that has escaped the minds of the aerospace industry and OOS hopes to capture this value. Figure 3–5 portrays the relationship between risk and uncertainty. Notice that risk is simply the downside of uncertainty, while rewards can be defined as the upside. Allowing a decision maker to react to future uncertainty, by way of future decisions, changes the range of possible outcomes by limiting, or eliminating, risk entirely (Saleh et al, 2002).

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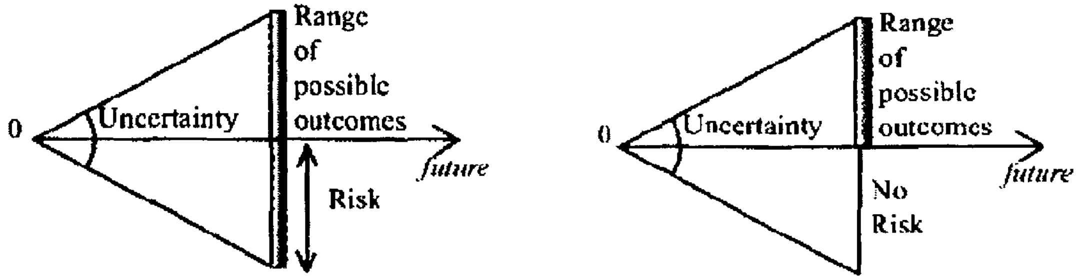
[5] Since there is the potential for this more powerful satellite to be ready at any point in time during the operational life of the initial satellite, there is a need to evaluate the full value of this option on the same time scale as the other options. It was discussed how previous research failed to take into account the potential for more valuable options. It was shown that because there is the potential for higher valued future options there is a need to be able to compare these high value options with low value options. The solution to the problem is to extend the time horizon of the valuation to encompass both the operation life of the initial satellite and the operational life of its *planned* replacement.



a) Without options: uncertainty means risk

b) With options: uncertainty means higher expected outcome

Figure 3–5: Uncertainty

It is well known within other industries that uncertainty has the ability to create value. Uncertainty is widely used in the stock market. While the stock market has apparent risk, the industry has developed some mechanisms that limit these risks and deliver asymmetric returns. In particular, the stock market has developed stock options which provide an investor with the right, but not the obligation to purchase stock in the future. By allowing the investor to make a decision, stock options create flexibility for the investor to react to future uncertainty in the market thereby generating value. Thus before rejecting the idea of creating value out of uncertainty, the aerospace industry should accept the idea that value can be generated through uncertainty. By adopting the mentality of designing for flexibility to support future uncertainty, the aerospace industry can capture additional value that is lost through traditional design.

The value of OOS can be determined by examining OOS as a customer's decision, or option, for satellite servicing. By adopting the assumption that OOS represents an option, the value of OOS can be determined in a similar fashion to finding the value of stock options. It is suggested that real options theory be used to determine the value of servicing. The underlying assumption behind real options theory is that, in the face of uncertainty, the decision-maker can make choices to maximize value. By designing satellites for servicing, the aerospace industry could have the right, but not the obligation to service its satellites. Thus, the value of designing for servicing over the traditional satellite design methods is the additional value that is delivered through the customer's ability to react to future uncertainty.

The real options approach for determining the value of servicing was previously used by Lamassoure and Joppin. Through following this process, one can vary the servicing price and determine the point at which the additional value of servicing is zero, which is the maximum servicing price. The maximum servicing price represents the point at which the customer is indifferent to servicing versus an alternative option. Thus by varying the servicing price and determining the maximum servicing price, one can determine when a satellite operator will service their satellite and when they will not service.

The next three chapters will look at three different examples servicing scenarios. Each chapter will determine the value of servicing for the customer as well as determine the customer's maximum servicing price. The first chapter will examine how to determine the customer's maximum servicing price in a case where servicing restores a commercial satellite's capability to a previous state. The next two chapters will look at the customer's maximum servicing price in cases where additional value is delivered through servicing; the first case will look at a commercial customer and the second case will look at a non-commercial customer. All three chapters represent possible servicing scenarios and are used as guides to how to determine the customer's maximum servicing price.

Chapter 4. Example: Asset Restoration

Typically, when a satellite fails, it cannot be repaired because the satellite cannot be accessed in orbit. To combat this problem, satellite designers have designed redundancy into satellites to compensate for the real risk of failure. But, can the access issue of satellites be addressed in a different way? Is there value in the capability to repair satellites? This chapter examines a case where a satellite operator wants to have the capability to restore the satellite to a previous state. This example focuses on life extension, but this same method could be applied to cases of satellite failure.

In todays satellite industry, it is common for satellite operators to lose value because the satellite has run out of propellant. Propellant is used on a satellite for various reasons, but a significant part of satellite's propellant is used to provide station keeping. Station keeping is vital to the operation of a satellite because station keeping allows a satellite to maintain its position in space. When satellites run out of propellant, the ability of the satellite to maintain its position is lost, the performance of the satellite decreases, and the satellite operator loses value. Eventually, if a satellite's ability to maintain position is not restored, the performance of the satellite will deteriorate to the point where the satellite is no longer useful. The focus of this example is to examine the case where an operator wants to restore the ability of their satellite to maintain its position after the satellite has reached the expected end of its operational life.

The overall purpose of life extension is to maintain a satellite's value by keeping the satellite operational beyond its expected design life. When the operational life of the satellite is extended by restoring the satellite's ability to maintain its position; this case of OOS servicing is commonly referred to as life extension. The maximum servicing price a satellite operator would spend on life extension is determined by finding the additional value provided by life extension. In particular, this example will focus on life extension that restores the ability of commercial GEO communications satellite to maintain position.

4.1. Presentation and Objectives

GEO communications satellites support the vast majority of the world's space-based voice, data, and video communications. Despite the high initial costs of these satellites, these satellites usually provide their operators with large revenues in the latter part of the satellite's operational life. The slow development of communications technology and the reliance on proven technology prevents GEO communications satellites from incorporating state-of-the-art technology. Thus, the value of any GEO communications satellites tends to remain fairly constant over time except for the occasional slight jump in value that results from the introduction of a new satellite bus design. Since the value of GEO communications satellites is fairly constant, the revenue potential of any given GEO communications satellites is limited only by the length of the satellite's operational life. The longer a GEO communications satellite remains operational, the more value it delivers to the operator.

Because the small chance of system failure due to the heavy reliance on redundant systems, a GEO communications satellite's lifespan is primarily fixed by the amount of propellant onboard the satellite. The propellant required by these satellites is used primarily to provide station-keeping for the satellite. Without the ability to provide station-keeping, a GEO communications satellite cannot provide communications service to the ground and hence provides no value to its operator. The amount of initial propellant for a GEO satellite is constrained during its design phase, due the high costs of launch and the common industry practice of minimizing mass in order to meet the mass and volume requirements of launch vehicles. As operators have begun to realize the potential value from longer operation, the design lives of satellites have begun to increase, see Figure 1–3. All in all, the typical lifespan of GEO communications satellites is about 10 to 13 years; this length of time is primarily limited by propellant and not component failure or technology obsolescence.

In an attempt to keep the mass of the system the same and have more revenue producing assets onboard, satellite designers have switched from chemical bi-propellant fuel to Xenon-electric propulsion in the more recent satellite designs. Xenon propulsion promises station-keeping ability at ~5 kilograms (kg) of propellant per year (Boeing, 2003). This would lead to about a 1/10th reduction in the propellant mass of bi- propellant satellites, which typically require 50 kg of propellant per station-keeping year. However, in light of the reduction in propellant mass, satellite operators have not used this mass savings as a way to add more propellant and provide longer lives for the satellite, as is shown by the slight increase in satellite design lives. The current Xenon-electric propulsion based satellite still provides a satellite with about15 years of operating life. Extending the operational life of satellites with electric propulsion systems makes little sense due to the small amount of mass required by these systems. If today's satellite provider really desired an increased operating life, they could simply add additional years of useful life at the cost of a few additional kilograms of fuel. Thus the focus of this example will not include satellites with Xenon-electric propulsion, but will focus only on determining the value from extending the life of the standard bi-propellant communications GEO communications satellites

4.1.1. Customer Need: Asset Restoration

Satellite operators believe that GEO communications satellites could continue to generate significant revenues if not for the fact that these satellites can no longer maintain their position. When GEO communications satellites run out of propellant, the value of these satellites reduces to zero. The ability to station-keep is the primary satellite capability that an operator wants to restore. This should not be confused with a need to re-fuel the satellite. Maintaining position is the customer's need, refueling is one way in which this can be accomplished. The motivation of satellite operators and some service providers is that, if a GEO communications satellite's station-keeping ability could be restored, the value of the satellites could be returned to a previous operating state.

4.1.2. Objective

The following example seeks to answer the following questions:

- What is the additional value that is delivered to the satellite operator through life extension?
- What is the satellite operator's maximum service price?
- What is the relationship between customer value and the price of servicing? (Linear, non-linear, etc...)
- What is the optimal length of life extension?
  i.e. how many additional operational years should the life extension service provide?
- Does the maximum servicing price vary with the length of the life extension?

4.2. Model Assumption and Characteristics

Life extension allows the satellite operator to gain additional value beyond the expected operational life of their satellite by extending the life of their satellite. To determine the additional value that life extension provides to the satellite operator, the option to service must be compared to the operator's baseline strategy. The operator's baseline strategy is defined as the normal operation of the satellite, i.e. launch followed by 10 years of operation and then decommissioning. The value of the baseline strategy will consist of the expected lifetime value of the satellite from launch to the satellites expected end-of-life. The optimal servicing strategy for the satellite operator is the baseline strategy with the option of extension rather than decommissioning. The value of the optimal strategy is the expected value of the satellite from launch to the new expected end-of-life that results from servicing. The difference between the value of the baseline strategy and the value of the optimal servicing strategy is the additional value that life extension provides to the satellite operator. The value from servicing is computed by using the evaluation method introduced by Lamassoure and Joppin that was discussed in Chapter 3.

4.2.1. Lack of a Serviceable Design

Is has been suggested that 50 or more GEO communication satellites operating in 2005 could have their operational lives extended through OOS (Long and Hastings, 2004 and Wingo, 2004). If this is true, then life extension of these satellites do not require the satellite to incorporate a serviceable design. If a serviceable design is not required, the satellite operator's decision process reduces to the one-part decision process discussed in Chapter 2. Before examining this case any further, a brief summary is provided on the ways in which life extension can be provided to current GEO communications satellites.

4.2.1.1. Refueling Approach

One way to restore the capability to maintain satellite position is to resupply the satellite with station-keeping propellant. Long and Hastings point out that GEO communication satellites have been shown in the past to have the ability to be refueled on the launch pad immediately before launch (Long and Hastings, 2004). The significance of this design feature is that these satellites have some feature that allows propellant to be removed from the satellite and later replaced. Because this feature allows one to accomplish this immediately before launch, the satellite must have the inherent ability to be fueled and refueled as a fully integrated satellite. Assuming this is the case, theoretically this should allow the same refueling process to be mimicked on-orbit. The limitation of this assumption is the need to mimic a human-dependent process in space. While space robotics technology may not as yet be up to this operation, both the Ranger and Robonaut programs show promise towards a robots ability to mimic humans in space.

4.2.2. "Space Tug" Approach

Another approach for restoring the satellite's position maintenance capability is not to refuel the satellite, but to supplement the satellite's inherent station-keeping systems with an external system. This method of life extension is the current thinking of one commercial satellite service provider, Orbital Recovery Corporation (ORC). ORC's life extension strategy does not involve refueling GEO satellites, but uses a less intrusive method of supplementing the satellite's station keeping capability by attaching to the target satellite's apogee kick motor. Orbital Recovery Corporation believes that a "Space Tug" type servicer can attach to the target satellite and supplement the satellite's station-keeping capability (ORC,2004), (Wingo, 2004). This method differs from the refueling method because it requires that the servicer become permanently attached to the target satellite in order to accomplish the mission.

4.2.3. One-Part Decision Model

In both the "refueling" approach and "Space Tug" approach, the operational state of the satellite is maintained by restoring the satellite's station-keeping capability. In both cases, the design of GEO communications satellites supports life extension even though the target satellite was not initially designed to support servicing. Unlike the two-part decision process, the customer is not forced to make a decision concerning the design of a serviceable satellite (See Figure 2–4). Because a serviceable satellite is not required, the additional value created by the life extension of GEO communications satellite can be evaluated using the one-part decision process.

In the one-part decision, process the satellite operator's decision process only consists of the decision to service the satellite, replace the satellite, do nothing, or decommission the satellite. The satellite operator will choose the branch of the decision tree that provides the greatest additional value. Because the value before the initial decision to service remains unchanged, the operator's optimal strategy is dependent only on the value generated by servicing after the first decision point.

4.2.4. Effect of Servicing

To determine when a customer should extend the life of their satellite, the focus of this analysis is on the additional value that can result from the optimal life extension strategy. The decision to decommission provides no additional value, while the decision to extend the life of the satellite has the potential to provide additional value. Although the satellite operator has the option to replace the satellite, which could provide greater value; the replacement option is not considered in this analysis. The reason for excluding the replacement option is that this example is looking only at the additional value that can be attained through asset restoration. Replacement would likely result in the launch of a new more capable satellite and therefore would represent an asset augmentation case.

If life extension provides positive value to the customer (greater than zero), a feasible market for the life extension of GEO communications satellites exists because more value can be attained through servicing than alternative options. The maximum servicing price that a satellite operator would be willing to pay for life extension results from varying the servicing price until the point at which the operator is indifferent to life extension versus decommissioning. The maximum servicing price theoretically represents the point at which the value from the option from life extension is zero.

4.2.5. Satellite Characteristics

Table 4-1: GEO Communications Satellite Characteristics

Characteristic	Value
Program Start	1994
Launch Date	1997 (Aviation Week. *2002*)
Expected End of Life	2011 (14 year expected life)
Operational Cost	10% initial annual revenue (McVey, 2002, pg 79)
Total Initial Costs	$206M (Estimated), (Intelsat 801, 2003)
Number of Transponders	76 Total (64 C-Band, 12 Ku Band) (Aviation Week. *2002*)
Initial Revenue / Transponder	$2.16M / year (FY $ 2000) (McVey, 2002, pg75)
Inflation Rate	2 %
Internal Rate of Return	8 %
Communications Market Volatility	10%
Market Drift	- 4 % (Bonds et al., 2000)
Years of Additional Life Provided by Extension	1 year and 3 years

The specific characteristics of the target satellite were modeled after the Intelsat 801 satellite. Intelsat was developed by Lockheed Martin and based on the GE-7000 platform. Intelsat 801 was launched in 1997 and had an expected operational life of 14 years. Intelsat 801 consists of 76 commercial communications transponders comprised of 64 C-Band and 12 Ku Band 36Mhz equivalent transponders (Aviation Week. *2002*). Table 4-1 summarizes the characteristics used to describe the customer's satellite.

4.2.6. Baseline Strategy

The baseline strategy for the satellite operator consists of the originally planned operation of Intelsat 801. The baseline consists of procurement of the satellite in 1994, launch of the satellite on an Ariane 4 in 1997, an operational life of 14 years, and an expected decommissioning in 2011. At the end of Intelsat 801's operational life, the satellite will be placed in a graveyard orbit to make room for its replacement satellite.

4.2.7. Uncertainty/Underlying Market

The market for Intelsat 801 was assumed to be the commercial communications market. It was assumed that the satellite's underlying market was based on the annual revenues generated by a single 36MHz equivalent transponder, regardless of the transponder frequency. The market was assumed to have an initial market value of $2.16M per year per transponder (McVey, 2002). The only uncertainty in the analysis was assumed to be the change in the annual revenues generated by a transponder. The uncertainty about the change in annual revenues was modeled using the log-normal binomial tree distribution. The market volatility was assumed to be 10% per year and an overall market drift was set at -4% per year (Bonds et al, 2000). The step size of the binomial tree was based on one year intervals based on the market data that was available.

4.2.8. Time Horizon

The time horizon for the analysis was set at 10 years beyond the design life of the satellite (2022). This value was chosen arbitrarily, but it is believed that any satellite would begin to experience component failure before an additional 10 years of operational life have been exhausted.

4.2.9. Decision Points

The first decision point concerning life extension occurs at the satellite's end-of-life (2011). From then on, the frequency of the operator's decision to service is a function of the form in which the servicing is provided. For instance, a satellite operator could be given the option of a single additional year of life through refueling. Here a service provider could only supply enough fuel so that the station-keeping ability of the satellite was maintained for a single year. By providing only a single year of life, the satellite operator to is forced to make a decision concerning extending the life of their satellite or decommissioning their satellite annually. This, however, is only one scenario.

Alternatively, the satellite operator could be provided with 10 years of extended life. This case would represent ORC's plan for providing life extension using the "Space Tug" approach. Recall from Chapter 1 that ORC's plan is that the ConeXpress servicer will be capable of supplementing up to ten years of station-keeping ability for a target satellite. In this case, given the time horizon chosen in the model the satellite operator would only have to make one decision concerning life extension. This decision would take place only at the satellite expected end of life (2011).

While the one-year and ten-year life extension scenarios are examples of possible extended operational lives provided by servicing, the satellite operator is not forced to base the decision on the additional life provided by servicing. Recall that the satellite operator and the service provider are separate entities. Therefore, the decision process and valuation of life extension are separate as well. The service provider therefore needs to determine which servicing length works best for the customer and then have the provider design a servicer to match. This, however, should not occur in the opposite direction. The service provider should not dictate what the customer wants. This would go against the idea of a customer-centric valuation approach and is one of the reasons why OOS providers do not exist today.

4.2.9.1. Time Step

The more decisions that a satellite operator makes concerning the operation of the satellite the more flexibility the operator will have to react to future uncertainty. It was assumed that a satellite operator would prefer to make a decision regarding servicing the satellite as often as possible. By making a decision to service as often as possible, the satellite operator is able to fully capture the flexibility provided by OOS. Increased flexibility allows the satellite operator to capture the maximum amount of value available through life extension. To limit additional uncertainties in the analysis, the time steps of the uncertainty parameters were set at annual year increments. This is because a customer's decision process is tied to the binomial tree used to describe the market uncertainty and one year is the smallest time step used in the binomial tree. As a result, the decision points concerning the operator's decision to extend will occur in years 2011, 2012, 2013 … 2021.

4.2.10. Operational States

Four operational states for the satellite exist in the analysis, the states are: End-of-life (EOL), Decommissioned, Just Serviced, and Waiting.

- The "End-of-life" state of the satellite represents the point at which the satellite has run out of the ability to perform station-keeping. This state is assumed to be the initial state of the analysis since the prior operational states of the system do not matter in determining the additional value provided by life extension.

- The "Decommissioned" state of the satellite represents the operational state where the life of the satellite has not been extended. The satellite is assumed to be placed in a graveyard orbit and as a result provides no additional revenues and requires no additional costs. Once a satellite has entered the "Decommissioned" state the satellite remains in that state for the remainder of the time horizon.

- The “Just Serviced” state represents that the operational state of the satellite where the operator has extended the life of the satellite by restoring the station-keeping capability of the satellite. Note: this is independent of the form of servicing (Refueling or Space Tug approach). The “just Serviced” state is only a single year in length and occurs immediately after the decision to extend. The state provides the operator with their expected revenues along with the expected costs of operating the system. In addition, the cost of servicing is assumed to be the cost required to switch from the “EOL” state to the “Just Serviced” state.

- The last state of the satellite is “Waiting”. While in this state a satellite is assumed to be waiting until its station-keeping capability has run out. A satellite can only be in the “Waiting” state if the length of life extension provided by the service is greater than one. A satellite enters a waiting state from either of two previous states: “Waiting” or “Just Serviced.” For instance, if servicing provided three years of life extension and the customer made the decision to do nothing in years two and three, the sequence of operational states of the satellite would be “Just Serviced” in year one and “Waiting” in years two and three. However, a satellite operator is always allowed to decide to service the satellite at the end of each year regardless of the length of life extension. While in the “Waiting” operational state the satellite is assumed to provide the operator with their expected revenues along with the appropriate operating costs. No switching cost are assumed to be required to go from either a “Just Serviced” or “Waiting” initial state to a “Waiting “ final state.

4.2.11. Risk

The risk associated with life extension is assumed to be zero regardless of the failure risk of the servicer. This is because, in the event of a failure, it is assumed that the responsibly would be placed on the service provider, not the customer, and without life extension the customer will gain nothing; thus the customer has nothing to lose by servicing. Robert Bernstien states “risk and time are on the opposite sides of the same coin, for if there was no tomorrow, there would be no risk (Bernstein, 1996).” However, this does not mean that no risk exists in the model. There is obviously risk for the service provider in the case of loss of the servicer or the creation of third party damage. But, since the customer and provider are separate, their risks remain separate. Without servicing the target satellite will have no future; therefore no risk exists *for the customer* with regard to servicing. Risks for the service provider are assumed to be accounted for as a risk premium that is incorporated into the servicing price.

4.2.12. Benefit Function

The benefit of operating the communications satellite is the annual revenue generated from the sale of communications services. The annual revenues of the satellite were computed by taking the product of the initial market value, the number of transponders on the satellite, and the relative change in the market. Because the change in the market is an uncertain parameter, the benefit of the satellite at any point will be an array of variables whose size is based on the number of possible uncertain market values described by the binomial tree distribution. Additionally, based on the probability associated with the market uncertainty, a discrete probability is associated with each element in the array. The expected benefit of any given uncertainty value for a given point in time is shown below.

Equation 4-1

$$EB_{i,T_j} = (\$2.16M)(\#transponders)(X_{i,T_j})$$

4.2.13. Costs

The initial costs were estimated at \$206M (FY 1997). This cost was based on the initial cost of procurement (\$76M), the launch costs (\$86M), the additional cost of insurance (\$27M), and estimated research, development, testing, and evaluation (RDT&E) costs (\$17M).The annual operational cost of the satellite was estimated at 10% of the satellite's initial annual revenue (~\$16.7M per year).

Equation 4-2

$$(C_{op})_{[T_{n-1},T_n]} = 0.1*(\$2.16M)(\#transponders)*\exp^{-\Re_{IRR}(T_{n-1}-T_0)}$$

Equation 4-3

$$C_{IOC} = (1 + \Re_{Ins})(C_{Satellite} + C_{Launch}) + C_{RDT\&E} + C_{Misc}$$

Table 4-2 lists the switching costs for going between the operational states of the satellite. It is assumed that a satellite will incur these costs when switching from one operational state to another.

Table 4-2: Table of Switching Costs for GEO Life Extension

	"Decommissioned"	"Just Serviced"	"Waiting"
"Decommissioned"	Zero	infinity	infinity
"Just Serviced"	Zero	infinity	Zero
"Waiting"	Zero	Servicing Price	Zero
"EOL"	Zero	Servicing Price	infinity

4.2.14. Value Function

Because the target satellite is a commercial GEO communications satellite, it was assumed that the satellite operator was a commercial entity. The value for the commercial satellite operator is strictly the additional profits from life extension. As a result, the value function for the extension of Intelsat 801 is the classic profit function;
Profits = Revenues - Cost. Equation 4-4 describes the value function in terms of the benefit function and the costs associated with the satellite.

Equation 4-4

$$\begin{aligned} EV_{[T_{n-1},T_n]}^{S_i-S_f} &= EB_{[T_{n-1},T_n]}^{S_1}(X_i)_{T_{n-1}} \\ &+ e^{-\Re_{IRR}(T_n-T_{n-1})}\left[p\left(EV_{[T_n]}^{S_{n1}}(X_{i+1})_{T_n}\right) + (1-p)\left(EV_{[T_n]}^{S_{n1}}(X_{i-1})_{T_n}\right)\right] \\ &- (C_{op})_{[T_{n-1},T_n]} - (C_{switch})_{T_{n-1}}^{S_i-S_f} \end{aligned}$$

The expected value of life extension is then the expected value of the optimal strategy over the entire time horizon described in Equation 4-5.

Equation 4-5

$$EV_{Life\ Extension} = EV_{[T_{EOL}:T_H]}^{S_{EOL} \to S^*}$$

4.2.15. Utility Function

It is assumed that the satellite operator's risk preference was based on the expected benefit that would be derived by extending the life of the satellite because no risk exists with regard to the loss of potential future revenue. By basing the decision to service on the expected future value, the satellite operator is portrayed to have a "risk-neutral" risk-preference. As a result of the risk-neutral preference, the satellite operator's perception of value is unaltered. Thus the utility function has no effect, i.e. a scalar value of one, on the operator's value function.

4.3. Results

The value that a customer will receive from servicing is a function of the servicing price associated with life extension. If the servicing price is high, one would expect that the cost would cut into the customer's profits, thus decreasing value. If the servicing price is low, one would expect the opposite effect to occur. The customer will make the decision about life extension based on the cost of servicing and the value delivered by the option for life extension. Because uncertainty about the future can only predict change in the underlying market, one cannot determine ahead of time the actual value of life extension. The only way for the value of servicing to be known is for the decision-maker to be at the decision point in the future. However, by using the probability distribution associated with the binomial tree distribution for the market uncertainty, one can calculate the expected value that a customer would received from life extension.

4.3.1. Single Year of life Extension

Figure 4–1 shows the expected additional value provided to the customer by a life extension in annual increments. Figure 4–2 provides a closer look at the results in Figure

4–1 for clarity purposes. The value of servicing in Figure 4–2 only represents that additional value that could be obtained for up to seven (7) additional years of life extension. The X-axis represents the servicing price that a customer would spend on life extension. The Y-axis provides the additional value, in this case the profits that a customer would receive from life extension, as a function of the servicing price. Each line in the figures represents the additional value that could be obtained if the satellite's operational life was extended to the corresponding year. For example if servicing resulted in a life extension of five years, the additional value from life extension as a function of the servicing price would be represented by the 2016 line.

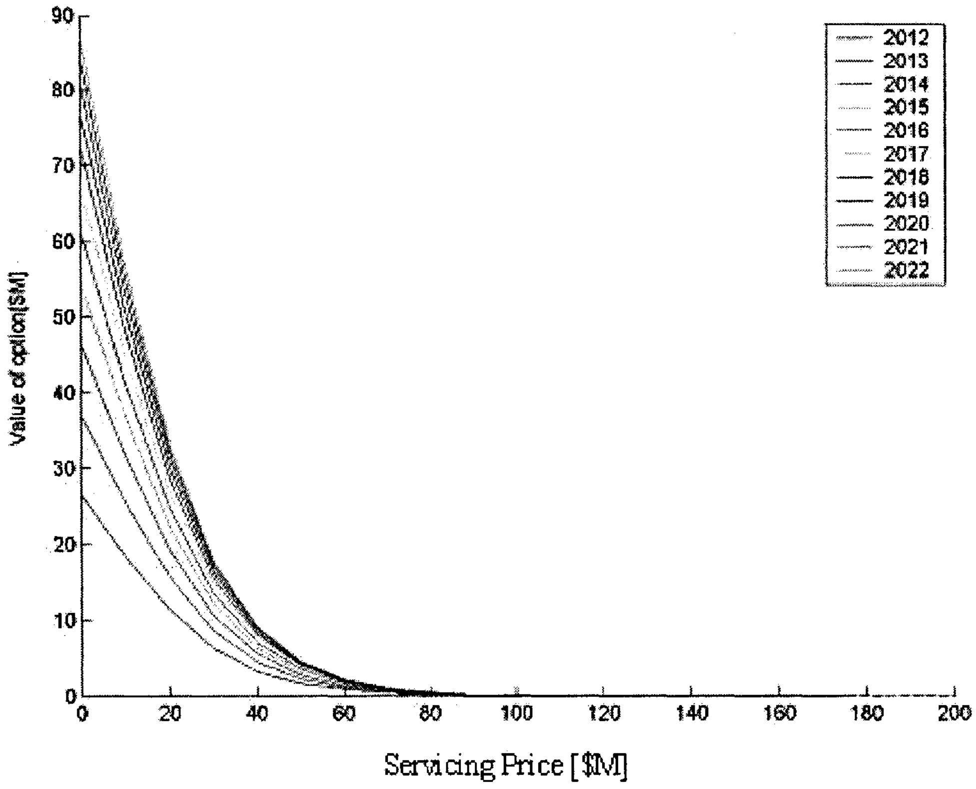


Figure 4–1:

Additional Value Provided Through Multiple Single Year Life Extensions (10 yrs)

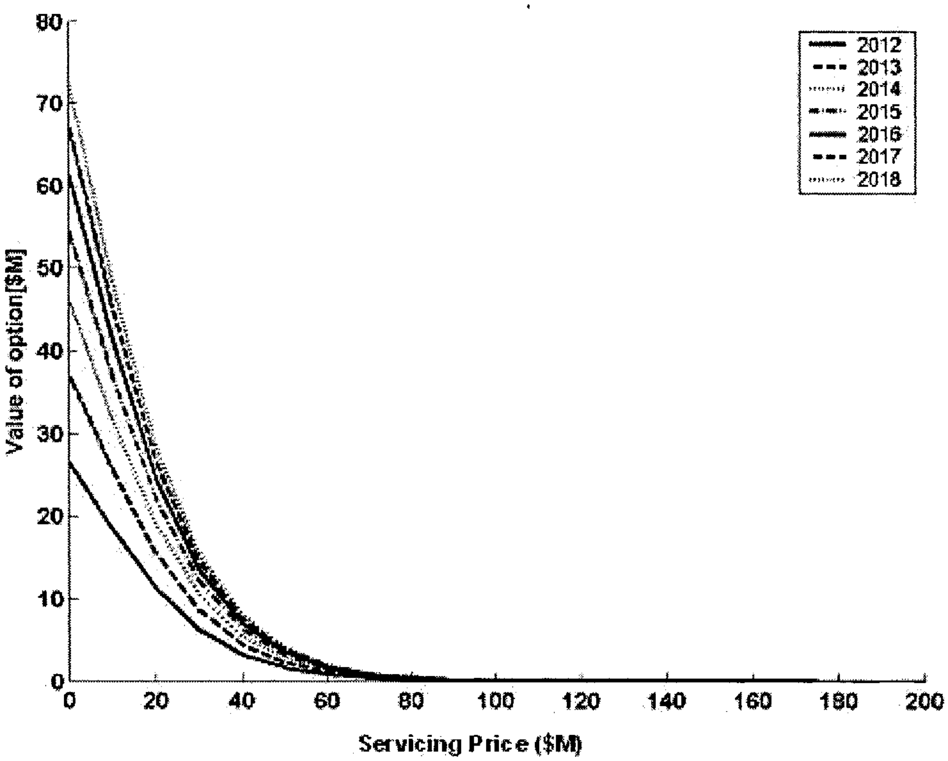


Figure 4–2:

Additional Value Provided Through Multiple Single Year Life Extensions (7 yrs)

By using Figure 4–2, a satellite operator is able to determine the expected profits from life extension based on the servicing price. For example, if a customer paid $10M for an extension of one additional year (2012 line), the customer could expect that option to be worth ~$19M. The servicing price, $10M in this case, has already been taken into account in the calculation of the value. Continuing with the example, a customer could expect to receive about $50M in profits by extending the life of their satellite six times (2017), paying $10M annually for servicing.

The maximum servicing price can be determined by finding the point at which the additional value from life extension (Y-axis) is zero. Figure 4–1 and Figure 4–2 indicate that the value of the life extension never actually reaches zero, but the value of the life extension approaches zero as the servicing price increases. It is clear that when the servicing price is above $100M, the value of life extension is very small. Thus one could assume that the maximum servicing price is about $100M.

4.3.1.1. Explanation of the Non-Linear Relationship Between Option Value and Servicing Price

The results in Figure 4–2 display a non-linear relationship that occurs between the expected value of the option and servicing price. This non-linear relationship arises from two characteristics of the servicing case:

1) Future profits are discounted to similar year dollars, which creates a compound discounting relationship between option value and time. The effect of discounting can be seen in the non-uniform increase in the option value for any fixed servicing price. For example, at an annual servicing price of $10M, the value of the option is $19M for one year of additional life, $26M for two years, $32M for three, and about $50M for seven years. As additional years of operational life are provided, the incremental increase in option value provided by an additional operational year decreases with time.

2) The log-normal assumption of the market uncertainty creates asymmetric predictions of future market values. This assumption bounds the range of potential market value between zero and infinity, which in fact is a good prediction of commercial markets. But, at the same time this assumption creates what may appear to be misleading predictions of strictly positive option value. These misleading predictions are a result of the real option analysis used to determine customer value.

The real options approach allows customers to limit losses, thus in this case the value of the option is always between zero and infinity (negative option values would result in a decision to decommission, which has a value of zero). Since the market forecast growth is bounded by infinity, extremely high servicing prices can still result in valuable options. Thus extremely high market values, although possible, have an extremely low probability of occurrence. When the expected value of the option is calculated using this unlikely event, the option value will always result in a positive value. As a result the value of the option in Figure 4–2 never reaches, but approaches zero.

4.3.2. Multiple Year Life Extension

The life extension scenario was further analyzed by varying the additional operational life for both two and three year servicing scenarios. Here the servicing scenario was represented as the case where the customer is provided with two or three years of station-keeping capability as opposed to the single year provided by the single-year service case. Figure 4–3 shows the results of the two year case and Figure 4–4 shows the results of the three year case. The important difference to note in both figures is that, as the satellite is provided with more station-keeping capability, the additional value provided by the various EOL lines begins to separate in a staggered fashion.

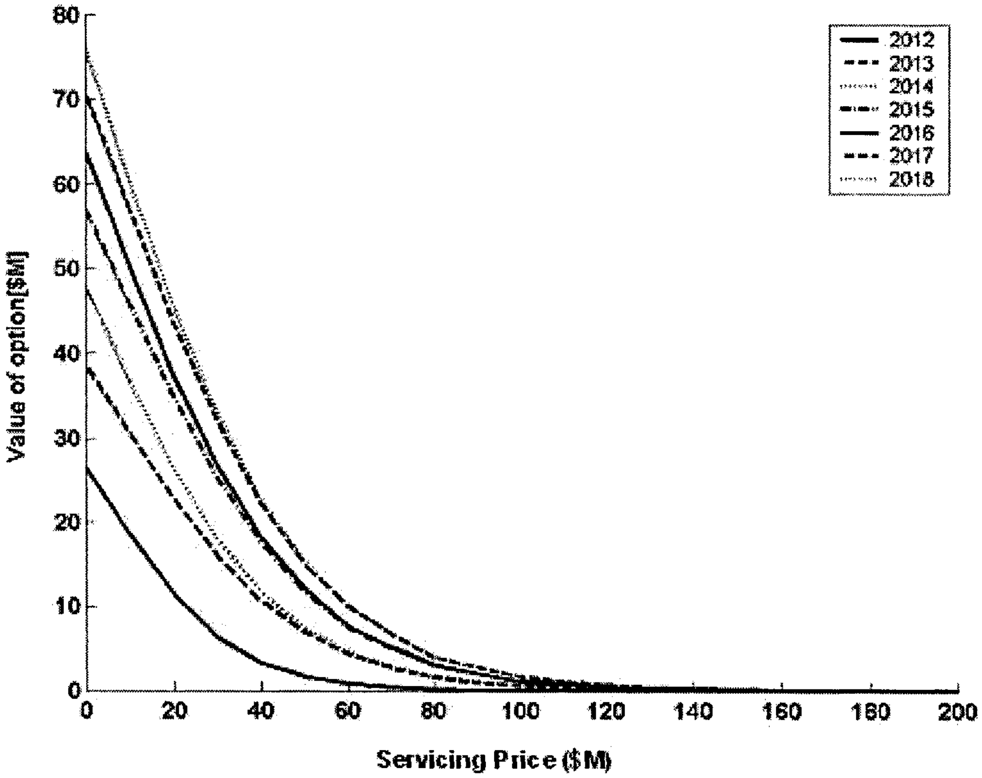


Figure 4–3: Additional Value Provided Through Multiple 2-Year Life Extensions

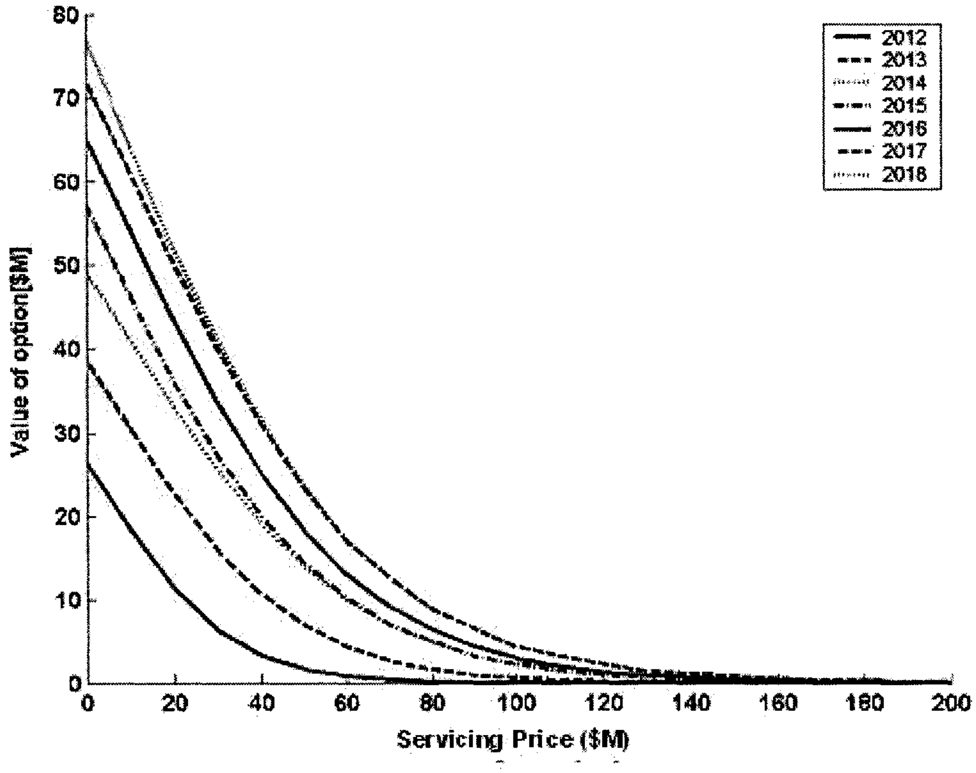


Figure 4–4: Additional Value Provided Through Multiple 3-Year Life Extensions

In the case where the customer pays for life extension once every three years, Figure 4–4, the option value for the second and the third operational years are a vertical shift up of the first additional operational year. When the number of operational years reaches the point where another service is required, the value of the option collapses back to the relationship found in Figure 4–2. This effect can be seen in the uniform separation between the 2012 and 2013 lines (second year of operation) and the 2013 and 2014 lines (third year of operation). The relationship between the 2014 and 2015 (first year of operation after second servicing) lines show the relationship between servicing price and value reverting back to the relationship found in Figure 4–2. The reasoning for this effect is that, in the second and third operational years, the satellite operator does not choose to extend the life of the satellite. Thus, no servicing cost is required and the servicing price does not undercut profits. This same effect can be seen in Figure 4–3, however in the two year life extension case, the staggering of the relationship between servicing price and option value alternates every two years instead of every three.

4.3.2.1. Effect of Multiple Life Extensions

In general, as the service length is increased, the value delivered to the customer for each period of extension increases. This effect can be seen by examining a theoretical six-year life extension case. By examining the cases with three different servicing lengths, six years of additional life could be delivered through three possible scenarios: 6-one year life extensions, 3-two year life extensions, and 2-three year life extension. Recall that when the servicing price was $10M per service and 6-years were provided through 6 one-year life extensions, the value provided to the customer was about $50M. In the case where six years of additional life is provided through 3-two year servicing missions, at $10M per service, the expected value of the option increased to about 57M. When six years of additional life is provided through 2-three year servicing mission, at $10M per service, the expected value of the option increased to about $65M. Thus the option value increases by providing longer operational lives with fewer servicing missions.

In addition to generating more value, the longer servicing length allowed for larger maximum servicing prices. In Figure 4–2 the maximum servicing price was about $100M per service. In the two year life extension case, the maximum servicing price ranges from $100M to $150M per service. In the three year life extension case, the range increases from $100M up to $170M per service. Despite the fact that higher servicing prices become feasible for longer periods of life extension, the overall shape of the relationship between the servicing price and the value delivered by servicing remains the same. Therefore, life extension remains significantly more likely the lower the servicing price.

4.3.3. The "True" Maximum Servicing Price

In Figure 4–2, the case where a single year of life is provided by each service, the customer's maximum servicing price is about $100M per service regardless of the number of additional years. However, it is unlikely that a customer would choose to service if such a low return on investment would result. One might expect that a decision maker would want some minimum return on their investment. For the moment assume that a satellite operator requires a minimum of 10% return on their investment in order to service. By requiring that a servicing mission results in at least a 10% return, the operator's maximum servicing price is no longer the point at which the value of servicing is zero. In light of the operator's threshold cut-off a new maximum servicing price needs to be computed, one which represents the maximum servicing price that a satellite operator would spend on servicing in order to receive the required level of return. For the purposes of this discussion, this servicing price will be regarded as the "true" maximum servicing price.

According to the operator's threshold cut-off, the "true" maximum servicing price would be the point at which the value of servicing was 10% of the servicing price. In the single year servicing mission scenario, Figure 4–2, a customer would likely choose to spend $40M on an additional year (2012 line) of operational life to order to gain $4M in profits ($44M in revenues). Thus the 10% threshold cut-off results in a "true" maximum servicing price of $40M for a single servicing mission. In the case where three years of additional life are provided by a single servicing mission, Figure 4–4, the "true" maximum servicing price is not represented by the 2012 line, but the 2014 line. This is because the satellite operator can receive three years of life for the price of one servicing mission. Thus the 10% threshold cut-off for a single servicing mission is calculated with respect to the value provided by three years of life extension. Therefore the "true" maximum servicing price for the three year life extension mission is about $70M for which the expected value is about $7M. It is important to emphasize that the maximum servicing price is still the point at which the value of servicing is zero.

The "true" maximum servicing price is the result of post-processing analysis; therefore the evaluation method discussed in Chapter 3 remains unchanged. For now the "true" maximum servicing price is the price a customer would decide to pay for servicing, while the maximum servicing price is the price at which the value of servicing is zero. Nothing is stopping a customer from choosing to service their satellite at a price equal to the maximum servicing price. Thus with regard to determining the feasible range of servicing prices, the maximum servicing price will still be used as opposed to the "true" maximum servicing price. The effect of the post-processing determination of the "true" maximum servicing price on a customer's decision to service will be discussed in more detail in Chapter 7.

4.4. Conclusions

Life extension is a unique example of asset restoration that does not require the design of a serviceable satellite. The appeal of life extension is that it restores a satellite operator's value under circumstances when this value would have otherwise been lost. An advantage of the evaluation method by which the additional value of this service is determined is that the solution is not a function of the form of servicing. Life extension could be achieved by satellite refueling or by permanently attaching a space tug; either solution fulfills the same customer need. The important factor is not the servicing method but the value that is delivered by the service.

Overall the result of the example shows that life extension becomes more feasible as the servicing price decreases. While higher servicing prices make sense in certain situations, these prices represent less probable future situations. The most critical finding of the life extension example is that the relationship between option value and servicing price is not linear. While a linear relationship might be expected, due to the classic profit equation: Profits = Revenues – Cost, the relationship between value and servicing price was higher-order in nature. The resulting relationship shows that while high servicing prices may be feasible, the customer's value from servicing does not begin to dramatically increase until the servicing prices are much lower. On the one hand, if a service provider has low servicing prices then slight increases and decreases in the servicing price can have a dramatic effect on customer value, thus making OOS more attractive. On the other hand, if the servicing prices are high slight increases and decreases in the servicing price will result in little change in the customer's value. Thus, the lower the servicing price charged by the service provider, the greater the chance of a feasible OOS market.

By understanding the additional value that can be delivered through life extension and its relationship to servicing price, a provider can design servicing architectures to meet the market demand. Chapter 8 will walkthrough how a service provider goes about deciding on a servicing architecture to meet customer demand in the case of end-of-life extension of a commercial GEO communications satellite.

Chapter 5. Example: Asset Augmentation – Commercial Customer

One of the major benefits offered by OOS is the concept of upgrades. Satellite upgrade is the idea of replacing components or payloads onboard a satellite with new more capable components. The goal of upgrading is to provide additional value to the satellite operator by increasing the value delivered by the satellite. By upgrading, a satellite provider is able to integrate new technologies as they become available. Upgrading has the potential to deliver the additional value provided by new technology that would have been lost while waiting for the current satellite to reach its end-of-life before launching a replacement. Since satellite upgrades seek to increase the value of an existing satellite, upgrades can fulfill a customer's need for asset augmentation.

Unlike the previous life extension example, upgrading a provider's satellite is much more complex and is likely to require that satellites be designed for servicing. Because of this requirement, the satellite operator has two decisions to make. The first decision is whether to design a serviceable satellite and the second decision is whether to service. Because the decision to service is in the future, the satellite operator can only predict the value that would result from upgrading. If the satellite operator believes that the upgrade of new technology will deliver more value than alternative options, the operator will design a serviceable satellite. Thus, the examination of the asset augmentation case is not primarily aimed at determining if a satellite operator should service; the case is focused on how to design the satellite.

Chapter 4 examined the additional value that could be delivered through the restoration of a commercial GEO communications satellite. This chapter will again examine the case for a GEO communications satellite, but will focus on the additional value that could be delivered through augmentation of that asset. It was pointed out earlier that technology development in the area of GEO communications is generally a slow process and that technology has not vastly changed over the past decade. In response, satellite designers focused on the development of improved satellite bus technology with the hope that improved bus technology would allow for more transponders to be placed onboard a satellite. Thus, operators are able to gain greater value by placing more transponders onboard a new satellite. This chapter aims to test this hypothesis and determine if the additional value that could be provided through upgrades outweighs the additional value delivered through more powerful satellite bus design.

5.1. Presentation and Objectives

In this example, a commercial satellite operator seeks to deploy a new satellite. The operator would like to provide the satellite with the capability to be serviced, but is not sure if the design will maximize the lifetime expected value. It is the goal of the satellite operator that a serviceable satellite will be able to provide additional value by integrating new technology as it becomes available. By integrating technology earlier, the operator believes that additional value will be generated versus waiting for the additional value to be delivered by a new satellite design. Therefore, if the satellite operator believes that the upgrade of new technology will deliver more value than a replacement satellite, the operator will design a serviceable satellite.

However, the operator has other options. While an operator could seek additional value through either new technology upgrades or new bus technology, the satellite operator also has the option of doing both. The use of both new technologies would result in a more powerful replacement satellite. This more powerful satellite could consist of new satellite bus technology that would allow for more value generating payloads. At the same time, the value generating payloads could be improved through the new technology that was used in the satellite upgrades. To pursue this option, the satellite operator would not have to design a serviceable satellite because this satellite would be a replacement. For a customer to launch a more powerful replacement satellite, both the new technology and new bus technology would need to be developed at, or before, the customer's decision for replacement.

The focus of this example is to determine when servicing provides more value than the alternatives. If the satellite operator believes that upgrading will result in the greatest value, the operator should design a serviceable satellite. If the operator believes that an alternative approach is more valuable, the operator should not design a serviceable satellite. The question that needs to be answered is under what circumstances should a satellite operator design a serviceable satellite and under what circumstances should the operator pursue a more valuable alternative.

It is assumed that the satellite operator has a good idea of the uncertainties associated with the development of all new technology and the underlying satellite market. Once again, the price associated with upgrading the serviceable satellite is unknown. The purpose of this example is thus two-fold; 1) Determine the customer's range of servicing price with respect to the upgrade of the serviceable satellite. 2) From the range of servicing prices, determine the maximum servicing price below which a satellite operator should initially design a serviceable satellite. The maximum servicing price is determined by finding the servicing price below which a serviceable design provides the same value as a non-serviceable design. The value of upgrading is the additional value over all other customer options, not just the baseline. As a result, the servicing price at which the value of OOS is zero once again represents the maximum servicing price below which an operator would initially design a serviceable satellite.

5.1.1. Customer Need: Asset Augmentation

The example examines cases where a satellite operator seeks to generate additional value by upgrading the satellite with new technology (unit-value increase). Competing for the chance to deliver the most value is the operator's option to deploy additional value-generating payloads (unit increase) in the form of a new satellite or the development of a more powerful replacement satellite (unit-value and unit increase). All options seek to increase the satellite operator's value and therefore constitute an asset augmentation.

Unlike the life extension case, the upgrade case requires that a satellite be designed for servicing. The requirement of a serviceable satellite forces the satellite operator's decision process from a one-part process, found in Chapter 4, to a two-part process. The two-part decision process described in Chapter 2 can be found in Figure 2–3. This decision tree illustrates the customer's two-part decision process consisting of: 1) the decision to design for servicing or not and, 2) potential future operational decisions in reaction to future uncertainties. It was assumed that a satellite operator would not be given the opportunity to decommission a satellite due to fear of losing its entire market user base. As a result, at any point in time, a customer's options are to do nothing, deploy a new satellite (replacement or more powerful replacement), or service.

5.1.2. Objectives

Because a customer's future decisions can only be finalized in the future when market uncertainty has been resolved, the purpose of the decision analysis is to determine how a customer should initially design the satellite. On the one hand, the satellite operator will not design a serviceable satellite when the upper branch of the decision tree provides more value than the lower branch. On the other hand, the customer should design a serviceable satellite when the lower branch provides more value than the upper branch. By varying the only unknown for the satellite operator— the servicing price— one can determine the customer's maximum service price by finding the tipping point between the choice to design a serviceable design and a non-serviceable design. In addition to determining how the operator should design the satellite, the example examines how a satellite operator would choose to build a serviceable satellite based on the increase in satellite capability provided by transponder upgrades, the volatility of the underlying market, the risk associated with the service, the risk preference of the customer, and the readiness of the upgrades.

5.2. Model Assumptions and Characteristics

5.2.1. *Effect of Servicing*

By upgrading the satellite, a satellite operator will have a direct impact on the capability of the satellite. In the case of GEO communications, satellite capability is generally measured by the satellite's communications capacity. The communications capacity is a measure of the communications traffic, in Giga-bits per second, which a given satellite can handle. Due to the long transmission distance, all communications traffic that reaches a satellite must be amplified before being sent back to the ground. The combination of equipment required to amplify communications traffic within a given frequency range is commonly referred to as a transponder. This equipment includes the high power amplifier (HPA) and filters at the input and output of the amplifier to isolate the communications traffic. The frequency extent over which the transponder operates is commonly referred to as the transponder's bandwidth (Atrexx, 2002). The more transponders that a satellite incorporates, the more communications traffic the satellite can handle and the more value that satellite delivers to its operator. To increase the value of the satellite, upgrading seeks to increase the communications traffic that a given transponder can handle.

In Chapter 4, a transponder was assumed to have a fixed revenue stream based entirely on the market value. This example looks at changing the capability of these transponders. As a result of the change in the capability of the transponders, the assumptions in Chapter 4 are no longer valid. Thus, new capability and performance metrics for transponders must be used.

5.2.2. *Satellite Characteristics*

Table 5-1 describes the characteristics for the initial satellite and potential new satellites. The initial satellite is assumed to have a procurement cost of $150M, launch costs of $100M, a 15% insurance premium, and annual operations costs of 10% of the initial operating costs. Operating costs were assumed to be 10% of procurement cost of the satellite. Any new satellite is assumed to have the same cost parameters as the initial satellite. The cost penalty to design a serviceable satellite is assumed to be 20% of the procurement cost.

Table 5-1:
Commercial GEO Communications Satellite Characteristics

Characteristic	Value
Analysis Start Time (t_o)	2002
Analysis Stop Time (t)	2022
Planned Replacement, expected EOL for 1st satellite	2012
Initial Satellite Procurement Cost	$150M ($FY 2002), 10yr operational life
New Satellite Procurement Cost	$150M ($FY 2002), 10yr operational life
Launch Cost, regardless of satellite	$100M ($FY 2002)
Satellite Operating Cost	10% Satellite Cost ($15M/Yr)
Launch Risk	2%
Insurance ($\Re_{INS}$)	15%
Inflation Rate ($\Re_{INF}$)	2%
Internal Rate of Return ($\Re_{IRR}$)	8%
Interest Free Discount Rate ($\Re_{IFR}$)	10% ($\Re_{INF} + \Re_{IRR}$)
Mark Up for Serviceable Satellite - P_{markup}	20% [6]
Percent Small Terminals	25% (Bonds et al., 2000)
Percent Large Terminals	75% (Bonds et al., 2000)
Ku-band Large Terminal Bit Rate	1.1 bps/Hertz (Bonds et al., 2000)
C-band Large Terminal Bit Rate	1.1 bps/Hertz (Bonds et al., 2000)
Ku-band Small Terminal Bit Rate	0.5 bps/Hertz (Bonds et al., 2000)
C-band Small Terminal Bit Rate	0.29 bps/Hertz (Bonds et al., 2000)
Satellite 1&2: 10 Year Contracts	40%, $58M annually (1998) (Bonds et al., 2000)
Satellite 1&2: 1 Year Contracts	40%, $77M annually (1998) (Bonds et al., 2000)
Satellite 1&2: 3 Month Contracts	5%, $154M annually (1998) (Bonds et al., 2000)
Satellite 1&2: 1 Month Contracts	5%, $274M annually (1998) (Bonds et al., 2000)
Published Interest Rate for Satellite Repayment	5%
Payments Per Year for Satellite Repayment	4
Amortization Period for Satellite Repayment	5 Years
Times Per Year Interest Is Calculated for Satellite Repayment	4
Transponder for Initial Satellite	25 C-band & 25 Ku-band (36Mhz)
Transponder for New satellite	35 C-band & 35 Ku-band (36Mhz)

5.2.3. Baseline Strategy

The baseline strategy is the design and operation of all satellites according to the current industry practice. This includes the design of a non-serviceable satellite, operation of that satellite for its entire operational life of ten years, and finally replacement of that satellite when EOL has been reached. The replacement satellite that will replace the initial satellite will be another non-serviceable satellite that will be operated until its expected end-of-life.

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[6] No specific estimate of the cost of design for serviceability has been established. Carole Joppin suggests, in her Master's Thesis, that the cost of designing for serviceability is approximately 10%. For the purpose of this study, a significant mark-up of 20% is used.

5.2.4. Uncertainties

The asset augmentation scenario addresses three types of uncertainties. In addition to uncertainty in the underlying market, future decisions incorporate new transponder technology development uncertainties (potential unit-value increase) and new satellite bus development uncertainties (potential unit increase). Advancement in new transponder technology is assumed to increase the capability for each transponder onboard the satellite, thus increasing customer value. Advancement in satellite bus technology is assumed to increase the capacity of the satellite bus, allowing for additional transponders on a new satellite. It is assumed that any new transponder technology can be applied to any satellite on-orbit (given that is was designed for servicing), but that new bus technology can only be applied to new satellites.

A technology freeze of three years beyond the launch date is assumed on all technology. The technology freeze is meant to capture the assumption that regardless of the customer's actions the customer cannot affect the design of any new technology. In reality a customer can always speed up the development of new technology by increasing spending, but this effect was not examined in this study. As a result of the technology freeze, new technology will not be ready before the fourth operational year of the initial satellite. However, the readiness date for any technology after the technology freeze is uncertain. It is assumed that any technology ready after the first day of any given year can be deployed at the start of the succeeding year, or a subsequent year. As a result, the upgrade or replacement of the target satellite cannot occur until the fourth year of operation. Furthermore, it is assumed that a decision maker will have to wait two years between the decision to launch a new satellite and the deployment of that satellite in order to account for development.

Uncertainties associated with the readiness of new technologies were modeled with an exponential probability distribution (H.S.Ang and Tang, 1975). The mean recurrence time for the readiness of new satellite bus technology was assumed to be five years. The mean occurrence time of the new transponder technology will be varied in the analysis to see the differing effects of fast and slowly evolving technologies. Because each uncertainty represents different sets of underlying circumstances in the customer's decision analysis, the effects of the uncertainties were modeled using Monte Carlo simulation. In all test cases, the simulation was run 200 times; the resulting range of servicing prices were computed as the mean of the range of servicing prices in all the simulations.

5.2.5. Market Uncertainty

In the GEO communications satellite case, the underlying market is described as the selling price for an annual one Gigabit per second (Gbps) contract. The initial value of the satellite's underlying market (X_o) at the time of launch is computed by taking the weighted average for the various forms of satellite communications contracts. Commercial communications contracts typically exist in four forms: 1 month, 3 month, 1 year, and 10 year contracts. Each of these contracts has it own annual price. Historically communications contracts are quoted as the annual price for 1 Gbps of capacity. Thus the annual communications contract prices are based on market research, found in Table 5-1.

It was assumed that the total capacity of the satellite was distributed among the various communications contracts in the following manner: roughly 40% to 10-year, 40% to 1-year, 5% to 3-month, and 5% to 1-month. As a result of the distribution, the total load per satellite was assumed to be 90%. The remaining 10% of the satellite capacity was assumed to be held in reserve; therefore, this 10% provided no direct benefit to the satellite operator. After the initial expected price for 1 Gbps of capacity was computed, the underlying market was modeled as a log-normal binomial tree distribution. The market was assumed to have a -4% annual drift rate and the market volatility was varied so that the effect of market volatility on the customer's maximum servicing price could be examined. Since the value is a function of the amount of traffic that a single transponder can handle, all transponders on a given satellite were valued equally using a fixed bandwidth of 36MHz.

5.2.6. Time Horizon

Since there is potential for a more powerful satellite to be ready at any point in time during the operational life of the initial satellite, there is a need to evaluate the full value of this option on the same time scale as the other options. Chapter 3 discussed how previous research failed to take into account the potential for more valuable options. Due to the potential for higher valued future options, the capability is needed to compare the higher value options with lower value options. One solution to the problem is to extend the time horizon of the valuation to encompass both the operational life of the initial satellite and the operational life of its *planned* replacement

5.2.7. Decision points

The following example assumes that the customer has two decisions to make: 1) the decision to design a serviceable satellite and 2) the decision to service. Unlike the asset restoration example, it is assumed that the customer has only one decision regarding reaction to future uncertainty. The customer's initial decision to design a serviceable satellite is assumed to take place at the time of launch (T_o) and the operator's decision to service will be varied between the earliest point in time that new technology is available, year three, and the end of the initial satellite's operational life, year 10. By varying the decision to service through the satellite's operational life, the effect that time has on the customer's maximum service price can be examined.

5.2.8. Operational States

Because the operator's choice to decommission is not examined, the satellite has five possible states of operation. These states of operation are: Normal Operation (Initial Satellite), Normal Operation (Serviceable Satellite), Upgraded Operation, Normal Operation (New Satellite), and Improved Operation (New Satellite).

- *Normal Operation (Initial Satellite)* – Normal operation of the initial satellite follows the baseline strategy. The satellite is operated as normal, the value of the satellite is unchanged and the only satellite costs are operational costs.

- *Normal Operation (Serviceable Satellite)* - Normal operation of the serviceable satellite is identical to that of the normal operation of the initial satellite, except for one difference. The serviceable satellite has additional cost associated with being designed for servicing.

- *Upgraded Operation* – The upgraded operational state is the state where the satellite has been upgraded with new transponder technology. As a result, the value of the satellite increases due to the increased capacity. To reach the upgraded state, a satellite must be in the normal operation (serviceable satellite) state and the satellite operator must spend the additional cost associated with servicing.

- *Normal Operation (New Satellite)* - Normal operation of the new satellite follows the same operational state as normal operation of the initial satellite except that the new satellite has an increase in value due to the increase in the number of transponders.

- *Improved Operation (New Satellite)* - Improved operation of the new satellite follows the same operational state as normal operation of the new satellite except that, in addition to the increase in value due to the increase in the number of transponders, the improved satellite has an additional increase in value from the incorporation of new transponder technology.

5.2.9. Risk

In the event that a servicer caused a satellite failure, the satellite operator would incur a loss equal to the amount of the expected future revenue along with any remaining repayment costs associated with the purchase of the satellite. Risk is therefore viewed as a probabilistic reduction in value associated with the risk of servicer failure.

5.2.10. Benefit Function

The benefit provided by both the initial satellite and any new satellites is based on the satellite's total capacity. The capacity of any given satellite depends on the efficiency of its transponders, the number of transponders, and the operational band of the transponders. The incorporation of any new transponder technology on the satellite will be represented by a unit-value increase in the efficiency of each transponder by a given percent, ΔU. The development of new satellite bus technology will result in the new bus being able to handle additional 10 C-Band and 10 Ku-band 36-Mhz equivalent transponders.

The revenues generated by the customer's satellite are determined based on the satellite's total capacity and the annual market price for 1 Gbps. Since each transponder type has a different capacity, the satellite's total capacity is a combination of the number of each type of transponder on the satellite (N), the bandwidth associated with each transponder in Hertz (36MHz), and the efficiency (bps/Hz) over the frequency of each transponder. Equation 5-1 describes the total capacity of the satellite.

Equation 5-1

$$Capacity(Gbits) = (N)_{Ku}(36\text{MHz})_{Ku}(\text{bps/Hz})_{Ku} + (N)_{C}(36\text{MHz})_{C}(\text{bps/Hz})_{C}$$

The capacity for a particular transponder frequency is determined by the increase (if any) in the transponder efficiency (ΔU), the percentage of small and large terminals the transponder frequency serves (% TotalCapacity), and the efficiencies associated with communicating with these terminals (bps/Hz). Table 5-1 lists the percentage of large and small terminals and the associated data rate/Hz ratios used in this study. Based on other research, satellite capacity (C and Ku-band) is distributed such that 25% went to small terminals and 75% went to large terminals. The expected data rate capacity for a given frequency range (C or Ku-band) is determined by the product of the bps rate/Hz ratio for a particular ground station, the percentage of dedicated satellite capacity for that ground station, and any increase in efficiency due to new transponder technology. After this quantity is calculated for each type of ground terminal, the products are summed together to get an average data rate capacity for a given transponder (see Equation 5-2). Finally, the annual benefit for any period of time is computed using Equation 5-3.

Equation 5-2

$$(bps/Hz)_x = (1+\Delta U)(\%TotalCapacity)_{\mathrm{large,x}}(bps/Hz)_{\mathrm{large,x}} + (1+\Delta U)(\%TotalCapacity)_{\mathrm{small,x}}(bps/Hz)_{\mathrm{small,x}}$$

Equation 5-3

$$EB_{i,T_j} = (Capacity)_{T_j}\left(X_{i,T_j}\right)$$

5.2.11. Costs

Table 5-1 lists all of the associated costs for both initial and new satellites. The cost associated with developing new transponder technology was assumed to be independent of the customer, while the cost of developing new bus technology was assumed to be factored into the cost of the new satellite. Operating costs were assumed to be 10% of procurement cost of the satellite. The operating cost estimate in the life extension example was based on revenue and pricing data obtained through interviews conducted by McVey. For this example, revenues were calculated by a different method. It is reasonable to conclude that the operating costs for a GEO communications satellite would be similar in both cases. As a result, the annual operating cost was set at 10% of the satellite cost, $15M annually. This estimate is similar to McVey's result. In the life extension case, McVey's approach estimated the annual operating cost at about $15.5M. The total initial procurement costs are given by Equation 5-4.

Equation 5-4

$$C_{IOC,Serviceable} = (1+P_{mark\text{-}up})(1+\Re_{Ins})(C_{Satellite}+C_{Launch})$$

$$C_{IOC,Non\text{-}Serviceable} = (1+\Re_{Ins})(C_{Satellite}+C_{Launch})$$

Table 5-2 is a matrix of the switching costs for going between the operational states of the satellite. It is assumed that a satellite will incur these costs when switching from one operational state to another. Normal Operation (New Satellite) and Improved Operation (New Satellite) have been removed from the first column of the matrix because these two states can only be operational end states of the satellite.

Table 5-2:
Switching Costs between Operational States of Generic GEO Communications Satellite

	Normal Operation (Initial Satellite)	Upgraded Operation	Normal Operation (New Satellite)	Normal Operation (Serviceable Satellite)	Improved Operation (New Satellite)
Normal Operation (Initial Satellite)	0	Infinity	Cost of Replacement	Infinity	Cost of Improved Replacement
Upgraded Operation	Infinity	Infinity	Cost of Replacement	Cost of Replacement	Cost of Improved Replacement
Normal Operation (Serviceable Satellite)	Infinity	Servicing price	Cost of Replacement	0	Cost of Improved Replacement

5.2.12. Value Function

Because the target satellite is a commercial GEO communications satellite, it was assumed that the satellite operator is a commercial entity. The value of upgrading for the commercial satellite operator is the additional profit resulting from upgrading over the next most beneficial strategy. The value function for the commercial satellite operator that results from upgrading is:

Equation 5-5

$$\begin{aligned} EV_{[T_{n-1},T_n]}^{S_i-S_f} &= EB_{[T_{n-1},T_n]}^{S_1}(X_i)_{T_{n-1}} \\ &+ e^{-\Re_{IRR}(T_n-T_{n-1})}\left[p\left(EV_{[T_n]}^{S_{n1}}(X_{i+1})_{T_n}\right)+(1-p)\left(EV_{[T_n]}^{S_{n1}}(X_{i-1})_{T_n}\right)\right] \\ &-(Cop)_{[T_{n-1},T_n]}-(C_{switch})_{T_{n-1}}^{S_i-S_f} \end{aligned}$$

5.2.13. Utility Function

The utility function was defined with respect to the potential total program value. Utility was defined on an ordinal scale with a range of 0 to 1, with 1 representing the best case for the customer and 0 representing the worst case. In terms of the possible program values, the worst case was defined as a loss of $1B in revenue; conversely, the best case scenario was defined as profits of $3B. A "risk-neutral" preference was associated with a customer who based his decision on the expected value. Therefore, a risk neutral customer has a linear utility curve of 0 to 1 over the range of -$1B to $3B. A "risk-adverse" customer was defined to have a risk premium of $250M at a utility of 0.5 and a "risk-seeking" customer was defined to have a risk preference of $250M at a utility of 0.5 (De Neufville, 1990). When determining the customer's optimal strategy, the customer's value was converted into customer utility using the utility function. After the optimal strategy was determined, the utility value was converted back into the expected value so that the remainder of the decision process could continue. Equation 5-6 describes the three different customer utility functions with respect to potential value.

Equation 5-6

$$U_{Risk-Neutral,T_k} = (EV_{T_K} + 1000)/4000$$

$$U_{Risk-Adverse,T_k} = 1 - .25\left(EV_{T_K} - 9000\right)^2\left(\frac{1}{16000000}\right) + .5625$$

$$U_{Risk-\mathrm{Pr}one,T_k} = .25\left(EV_{T_K} + 7000\right)\left(\frac{1}{16000000}\right) - .5625$$

Equation 5-7

$$\begin{bmatrix} U(EV_{[T_n:T_{n-1}]}^{S_1\to S_1}(X_1)) & \cdots & U(EV_{[T_n:T_{n-1}]}^{S_1\to S_n}(X_1)) \\ \vdots & \ddots & \vdots \\ U(EV_{[T_n:T_{n-1}]}^{S_1\to S_1}(X_n)) & \cdots & U(EV_{[T_n:T_{n-1}]}^{S_1\to S_n}(X_1)) \end{bmatrix} = \begin{bmatrix} U(EV_{[T_n:T_{n-1}]}^{S_1\to S^*}(X_1)) \\ \vdots \\ U(EV_{[T_n:T_{n-1}]}^{S_1\to S^*}(X_n)) \end{bmatrix} \Rightarrow EV_{[T_n:T_{n-1}]}^{S_1\to S^*}$$

5.3. Sample Results

Figure 5–1 is a sample output from the commercial GEO communication satellite augmentation analysis. In this case, the unit-value increase provided from new transponder technology was assumed to increase the data rate/Hz ratio of a single transponder by 50%. In reality, this value would be extremely high, but this value is used to demonstrate its effect. The mean occurrence time for the readiness of the new transponder technology was assumed to be one year. The volatility of the market was assumed to be 20% (higher than one might expect- again used for effect), the risk associated with the loss of the satellite due to servicing was assumed to be 5%, and the decision maker was assumed to be risk neutral. In the event that a servicer caused a satellite failure, the satellite operator would incur a loss equal to the amount of the expected future revenues along with any remaining repayment costs associated with the procurement of the satellite.

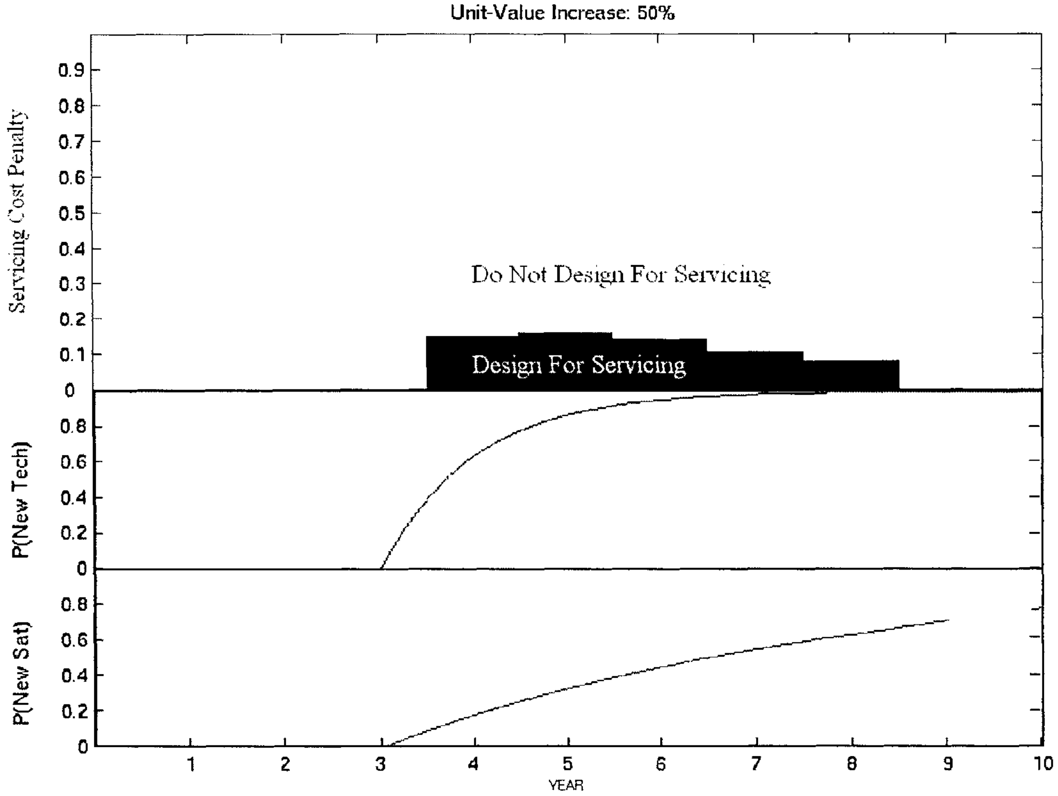

Figure 5–1:

Sample Output for the Commercial GEO Communication Satellite Scenario

Figure 5–1 is designed so that a decision maker can make a quick decision concerning the choice to design for servicing. The x-axis represents the decision year beyond the launch of the initial satellite. At each decision year, the customer can choose between the available options, depending on how the satellite was initially designed. Therefore, a decision maker who designed for servicing could choose to do nothing, replace, decommission, or service the satellite (see the lower branch of Figure 2–3) at the decision point. However, if the decision maker did not design for servicing, the option to service would not be available to the customer (see the upper branch of Figure 2–3).

On the Y-axis, Figure 5–1 provides three distributions with respect to time; P(New Sat), P(New Tech), and the servicing cost penalty (CP_{Ser}). P(New tech) represents the cumulative probability as a function of time for the readiness of the new transponder technology. Because of the imposed technology freeze of three years and the uncertainty about the readiness of the transponder technology, it cannot be known with absolute certainty that the transponder technology will be ready in year three. For later decision points, the probability of technology readiness increases and approaches certainty. Note that the cumulative probability only describes the expected readiness of one generation of technology. Additional generations of technology will be developed as time goes on, but in this case only the development of one generation of technology was assumed. P(New Sat), like P(New Tech), represents the cumulative probability as a function of time about the readiness of the new satellite bus technology. Recall that satellite bus technology allows the customer to incorporate additional transponders on future replacement satellites. In this case a decision maker can expect that new transponder technology will be ready before new bus technology. This is because of the assumption that the new transponder technology development occurs at a faster rate (occurrence time of one-year), than the bus technology (occurrence time of five years).

The distribution for the servicing cost penalty represents the mean change in relative program cost for which the decision to service provides the customer with the greatest expected value. The servicing cost penalty in each case was computed by determining the difference between the cost of the customer's baseline strategy[7] and the cost of designing an initial satellite to be serviced, along with any incurred cost resulting from the decision to service, relative to the customer's baseline strategy (See Equation 5-8). The servicing cost penalty is the fraction of the baseline costs that must be spent to pursue the optimal servicing strategy. It was assumed that the cost penalty associated with designing a serviceable satellite ($P_{Mark\text{-}Up}$), the cost of initial deployment (C_{sat}), the satellite insurance premium ($\Re_{INS}$), and the cost of operations (C_{op}) are all known. The cost associated with developing new transponder technology was assumed to be independent of the customer, while the cost of developing new bus technology was assumed to be factored into the cost of the replacement satellite. The only remaining unknown cost in the servicing cost penalty is the servicing price. Each value of the servicing cost penalty above the minimum incurred cost (assumed costs where the servicing price is $0) is calculated by varying the servicing price. Therefore, the distribution for the servicing cost penalty describes the range of servicing prices below which the customer should initially design the satellite for servicing.

Equation 5-8

$$CP_{ser} = \frac{C_{Serviceabl\ e\ Satellite} + C_{Servicing} - C_{Baseline}}{C_{Baseline}}$$

The purpose of examining the distribution is to determine whether a customer should design the satellite for servicing, not whether the customer should service. If the cost of servicing is such that the servicing cost penalty lies within the distribution, designing a serviceable satellite is probabilistically the most valuable strategy for the customer. The distribution then becomes a kind of "GO/No GO" gauge with respect to designing for servicing: Go, if the expected servicing cost penalty is within the distribution; No Go, otherwise. For example, in Figure 5–1 if the expected servicing cost penalty in year five was 0.1, the customer should design the satellite to be serviced. Since the distribution describes a range of acceptable servicing prices, the upper bound of the distribution

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[7] The baseline strategy is the decision not to design a serviceable satellite and to decide to do nothing when faced with future operational decisions.

represents the maximum servicing price a customer is willing to spend on servicing as a function of the decision year. Recall that the maximum servicing price is the point where the customer is indifferent to servicing versus the next best alternative strategy. From Figure 5–1, the customer's mean maximum servicing price is estimated using the following equation:

Equation 5-9

$$\text{ServicePrice}_{Max} = \frac{C_{Sat}\left(CP_{Ser} - P_{Mark\text{-}up}\right)\left[\left(1+\Re_{INS}\right)+C_{op}\sum_{t=t_0}^{t_n} e^{-\Re_{IFR}(t-t_0)}\right]}{e^{-\Re_{IFR}(t_k - t_o)}}$$

where t is the expected end-of-life year of the satellite, t_o is the initial launch year, t_k is the decision year, and $\Re_{IFR}$ is the customer's unique interest free rate.

Although the results in Figure 5–1 show that a feasible market exists if a customer expects to service during years four through eight, these results are only one example of a potential market. In fact, there are several design elements that can affect the feasibility of OOS. The effect of these elements was examined by performing a sensitivity analysis on their effect on the customer's maximum servicing price. The sensitivity of the customer's maximum servicing price was examined by varying the following parameters: transponder technology efficiency, market volatility, servicer risk, customer risk preference, and the speed of new technology development. The remaining graphs in this chapter display the maximum servicing cost penalty. A feasible servicing range exists for all servicing prices below the maximum servicing cost penalty shown in the graphs.

5.3.1. Sensitivity to New Transponder Technology Improvement

Figure 5–2 shows the effect of varying the increase in the transponder efficiency on the customer's maximum servicing price. The change in efficiency was varied from 10%, 30%, 50%, 70%, and 90%. Notice that an increase in efficiency of 10% (which is the most likely increase in efficiency given today's technology growth) is not large enough to create a feasible market. As the increase in efficiency from new transponder technology becomes greater, the range of servicing prices increases uniformly at all points in time. This linearly increasing pattern is likely the result of the linear dependence of the customer's value on the benefit generated by the satellite. In this case, the customer is a commercial entity. For commercial companies, value is usually computed using the classic function Profit = Revenue - Cost.

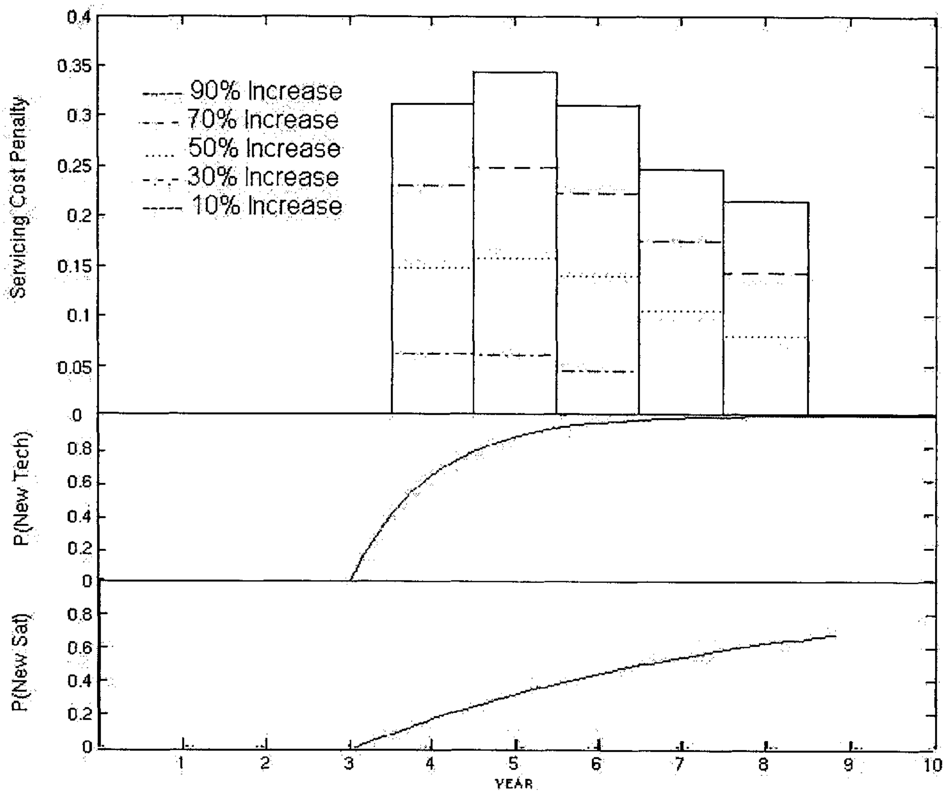


Figure 5–2: Effect of Varying Increases in Transponder Efficiency

It is reasonable to assume that, if there is a high correlation between the increase in performance and the benefit delivered by that increase, there will be a high correlation between the increase in performance and the customer's maximum servicing price. Therefore, to dramatically increase the customer's maximum servicing price, a customer should focus on the upgrade of technologies that significantly increase the customer's value. Since small increases in capability did not create a feasible market, servicing only makes sense when significant increases in the capability of the satellite are present.

5.3.2. Sensitivity to Market Volatility

Figure 5–3 shows the effect of varying the underlying market volatility on the customer's change in relative program costs. The annual change in market volatility was varied in 15% increments between 15%, 30%, 45%, 60% and 75%. Figure 5-4 shows that the maximum servicing price for all the volatilities remains about the same for earlier decision points in the satellite's operational life. However, highly volatile markets quickly become less attractive as a customer waits until later decision points. The decrease in the maximum servicing price for later decision points occurs because highly volatile markets have the potential for greater value. Recall that the most valuable option for a customer in this example is to replace the satellite with a satellite incorporating new transponder technology and new bus technology. The ability to deliver greater value through replacement is what drives down the price at which a customer is indifferent to servicing versus replacement. Therefore, there is a point at which a market can be too volatile to make servicing an attractive option.

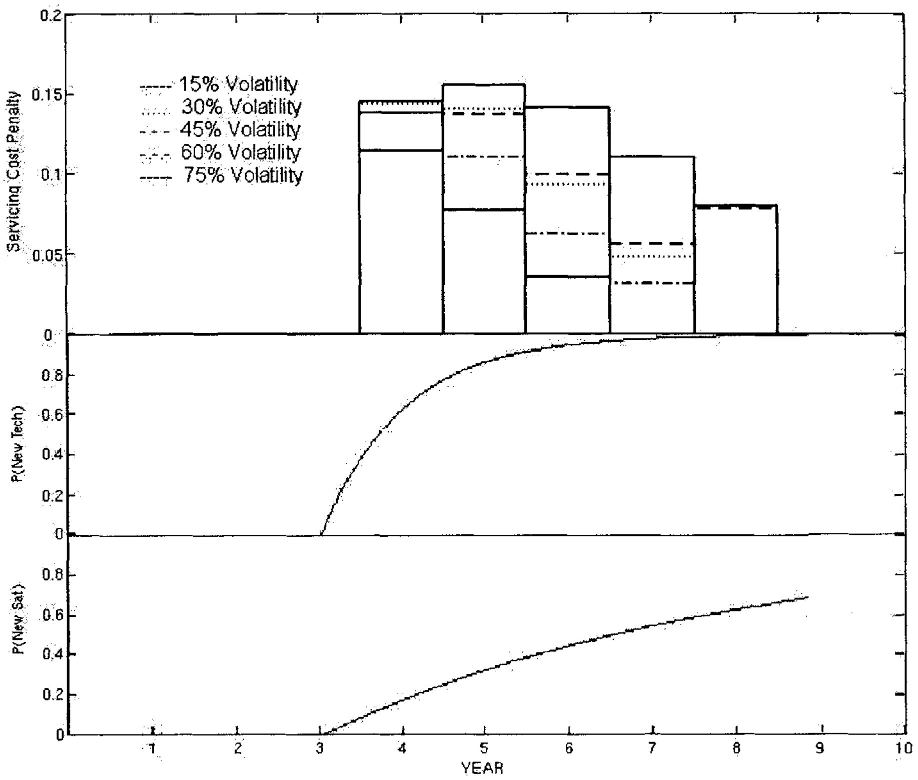


Figure 5–3: Effect of Varying Market Volatility

5.3.3. Sensitivity to Servicer Risk

Figure 5–4 shows the effect of varying the servicer risk on the customer's maximum servicing price. The service risk was varied from 0%, 5%, 10%, and 15%. In determining the value that OOS delivers to the customer, risk was assumed to be the chance that a satellite would be destroyed due to servicing and therefore represented as a probabilistic reduction in value. The analysis did not take into account the fact that a service failure could result in a partial failure of the satellite, thus only reducing the value of the satellite. The benefit of determining the effect servicer risk has on customer value is that a service provider can determine an appropriate level of risk associated with the servicer design while still providing value to the satellite operator.

In this particular case, a servicer risk of 15% is too high to create a feasible OOS market. Notice that as the servicer risk is increased, the range of potential servicing prices decreases fairly uniformly with respect to time. This effect is due to the assumption that risk is a probabilistic reduction in value. However, the magnitudes of the change between the different maximum servicing prices do not change linearly with the different levels of servicer risk. For example, the difference between the maximum servicing price between the 0% servicer risk and 5% servicer risk cases is not the same as the difference between the 5% servicer risk and 10% servicer risk cases. It is suspected that the cause of this relationship is related to the risk preference of the customer. In particular, in this case the decision-maker was assumed to be "risk-neutral". Therefore, as the servicing risk increased, a decision maker would choose to service less often, thus the expected value of the option decreases. If a decision-maker is portrayed using another form of risk-preference, for instance" risk-prone", the differences in value between different levels of service risk would differ from that of a "risk-neutral" decision-maker. Regardless of the true cause of this effect, the more risky the servicer, the less value it delivers to the satellite operator, and therefore the lower the maximum servicing price.

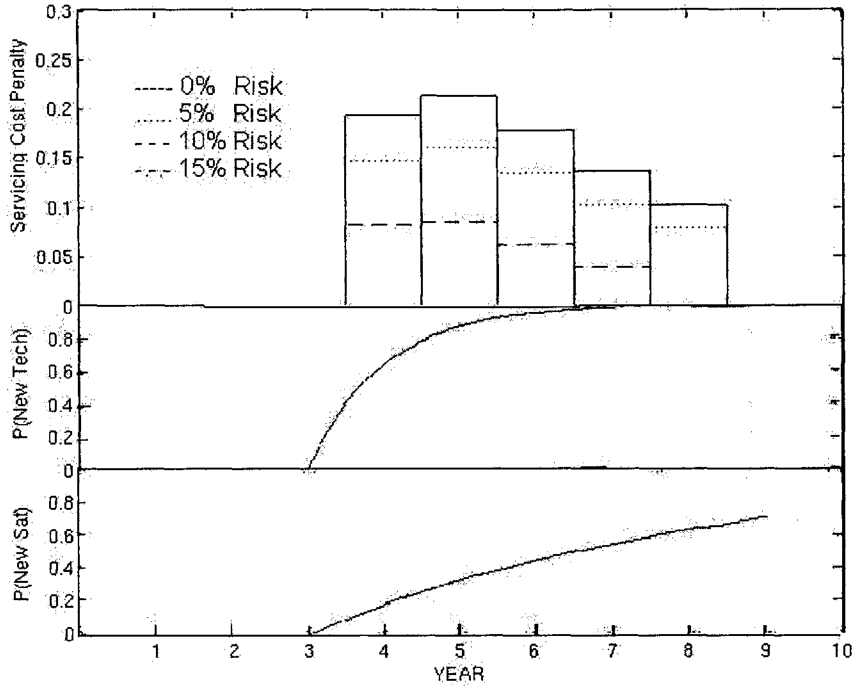


Figure 5–4: Effect of Varying Servicer Risk

5.3.4. Sensitivity to Customer Risk Preference

Figure 5–5 shows the effect of varying the customer's risk preference on the maximum servicing price. The customer's risk preference was varied between a "risk-adverse", "risk-neutral", and "risk-seeking" decision maker. (De Neufville, 1990) Utility theory was used to determine how risk preference would affect a customer's decision making.

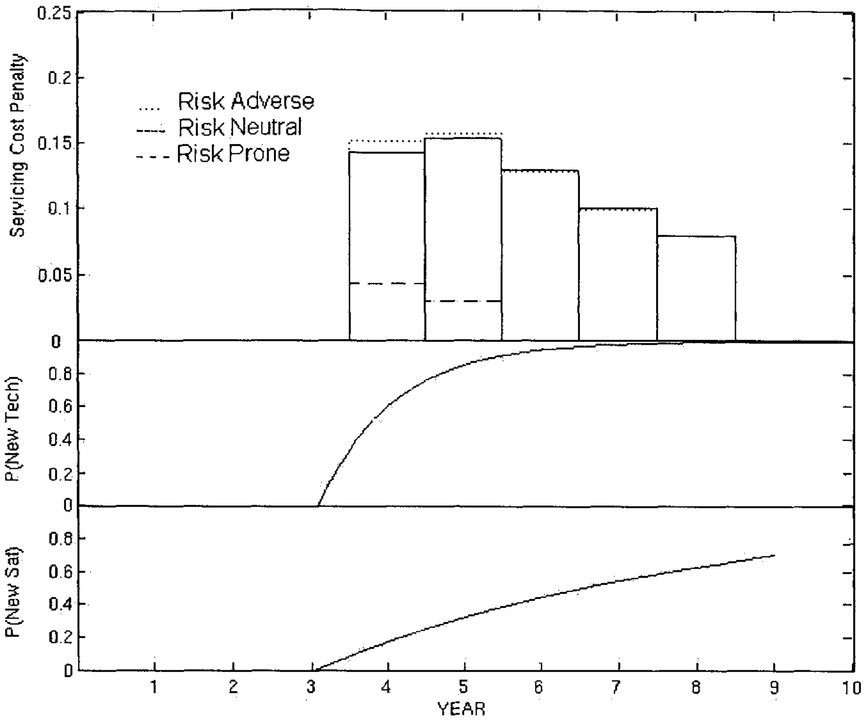


Figure 5–5: Effect of Varying Customer Risk Preference

From Figure 5–5, the distribution of the maximum servicing price is almost identical for a "risk-adverse" and a "risk-neutral" decision maker. However, the maximum servicing price for a "risk-seeking" decision maker is dramatically different. This dramatic difference is due to "risk-seeking" nature of the customer. "Risk-seeking" customers generally choose options that are probably less profitable, but have the chance of substantial rewards. Simply put, "risk-seeking" decision makers want to take risks. As was seen with the higher volatility example, the potential for greater rewards with servicing exists during the earlier part of the decision period. By waiting until later decisions points, a "risk-seeking" customer would tend towards more profitable actions such as replacement. As a result, "risk-seeking" customers are likely to choose to service earlier rather than later because earlier service events have the potential of greater long-term rewards. By varying the customer risk preference, it was discovered that "risk-adverse" and "risk-neutral" decision-makers have very similar maximum servicing prices. Thus, the "risk-adverse" decision maker in today's satellite industry should not be adverse to the idea of satellite servicing.

5.3.5. Sensitivity to Technology Readiness

Figure 5–6 shows the effect of varying the mean recurrence time of new transponder technology on the customer's maximum servicing price. The mean technology recurrence time was varied between one year, three years, and five years. From Figure 5-7, the faster the new transponder technology is expected to be ready, the more potential value it delivers to the customer. But, the benefit of fast evolving technologies dies out the longer a decision maker waits to implement the technology. Thus, OOS can provide value to the customer by allowing for the integration of fast evolving technologies earlier than could be accomplished with current satellite designs. Joppin comes to the same conclusion about fast evolving technologies in a study concerning the upgrade of the Hubble Space Telescope. The study discusses how the upgrade of multiple fast-evolving technologies leads to a significant increase in value (Joppin and Hastings, 2004).

Although fast evolving technologies have the potential to deliver greater value, the decision to upgrade technology must be acted on earlier rather than later if maximum value is to be attained. As a customer waits until later decision points, the difference in the value that fast-evolving technologies provide over slowly-evolving technologies decreases. The longer it takes a decision maker to act, the less valuable the benefit of fast-evolving technologies. The relationship between fast- and slowly-evolving technologies provides proof of the generalized notion that OOS provides value to the customer by allowing the customer to integrate new technologies into a system earlier than could be achieved through conventional satellite design.

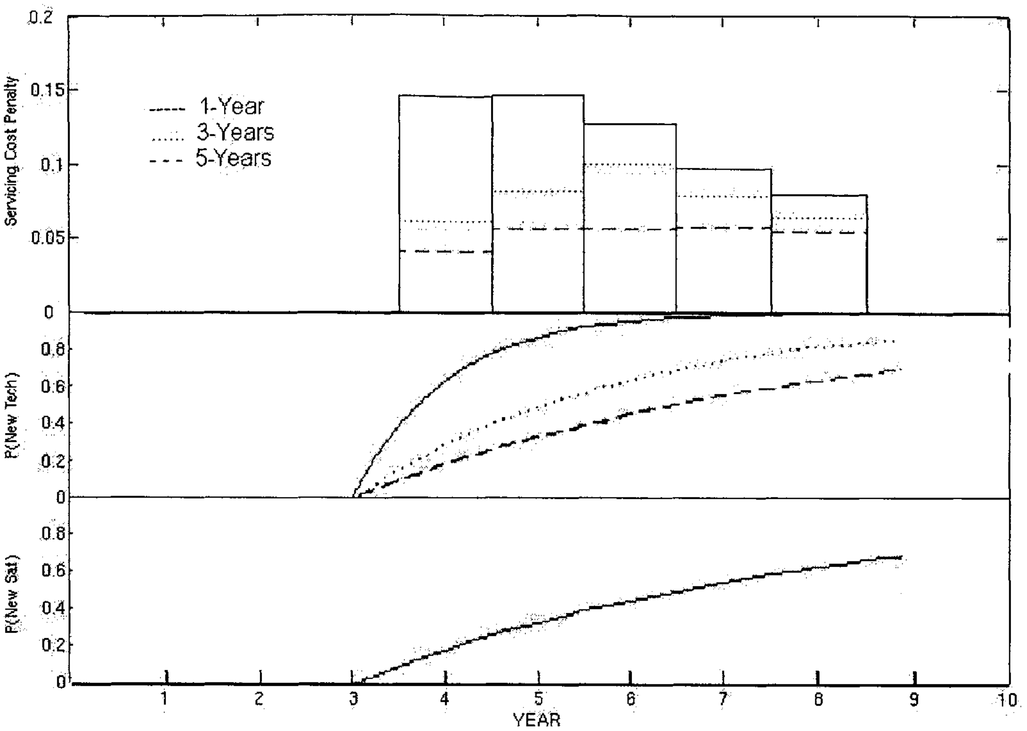


Figure 5–6: Effect of Varying Technology Readiness Time

5.4. Conclusions

The objective of this commercial satellite technology upgrade example was to determine the customer's maximum servicing price and to characterize the elements of a serviceable market. It was demonstrated that the customer's maximum servicing price depends on a number of the variables. The most significant variable that affects the customer's maximum service price is the increase in capabilities due to the incorporation of new transponder technology. Regardless of other factors in the model, if the increase in satellite capability from servicing is not significant enough, OOS for the purpose of asset augmentation seldom makes sense.

Examination of the effect of market volatility demonstrated that highly volatile markets do not make the best OOS markets. Highly volatile markets also make later decisions to service less valuable, thus earlier decisions to service make greater sense in all ranges of volatile markets. Servicer risk was found to have a uniform increasing/decreasing effect over the decision period making less risky servicing missions more feasible, as would be expected. With regard to customer risk perception, it was found that feasible OOS markets exist for customers who follow a "risk-adverse" or "risk-neutral" stance. "Risk-seeking" decision makers prefer potentially more valuable alternative actions such as replacement. Finally, when compared to slowly-evolving technologies, it was also found that fast-evolving technologies provide greater value to the customer the earlier the decision to service is made.

Through the examination of the asset augmentation case, it was found that satellite upgrades can provide additional value over traditional satellites designs. Based on this result, it might be concluded that the current design approach is not the best approach for maximizing value. However, this statement only holds true for a small range of servicing prices. For higher servicing prices, the design for servicing does not make sense and alternative options such as satellite replacement result in greater customer value. Thus, designing for a serviceable satellite is the best decision for the customer when the price of servicing remains low; in cases when the servicing price is high, a customer should design the satellite according to traditional methods. Chapter 6 examines the same effects on the maximum servicing price for the case of a customer who is a non-commercial entity.

Chapter 6. Example: Asset Augmentation – Non-Commercial Customer

Up to this point, the focus of this thesis has been on the servicing of commercial satellites. However, the use of space stretches far beyond that of commercial customers. While an initial OOS market may focus on servicing commercial satellites, a large majority of satellites do not derive direct monetary benefits for their operators. This does not mean that servicing cannot provide non-commercial customers with value. In fact, non-commercial customers may be the most likely candidates for servicing.

To determine if OOS is feasible for non-commercial customers, a service provider must be able to determine the non-monetary value servicing provides. One of the benefits of the evaluation methods discussed in Chapter 3 is its ability to determine value for satellite operators whether they are commercial or non-commercial. Recall that the value function for an operator is a function of many elements, which include the benefit provided by the satellite and the costs associated with the satellite. Thus the value for a non-commercial satellite operator is a function of benefits and cost. Therefore, by determining the costs associated with the satellites and the benefits created by the satellite, one can determine the value of servicing for a non-commercial satellite operator.

This chapter examines another augmentation example, but focuses on the case where the satellite operator is not a commercial entity. It is likely that the characteristics of a feasible markets found in Chapter 5 are not unique to the commercial case. This chapter examines this hypothesis, determines the characteristics of the non-commercial case, and compares these characteristics to the characteristics of the commercial case. Once completed, the results of this chapter and the previous chapter should provide a general set of characteristics that will aid in defining a feasible asset augmentation scenario. To determine the characteristics of the non-commercial case, this chapter examines the maximum servicing price that is associated with the upgrade of the GOES weather satellites.

6.1. Presentation and Objectives

The National Oceanic and Atmospheric Administration (NOAA) uses GEO observation satellites to predict and observe weather formations over the United States. The GOES satellites provide a constant vigil for the atmospheric "triggers" for severe weather conditions such as tornadoes, flash floods, hail storms, and hurricanes. When these conditions develop, the GOES satellites are able to monitor storm development and track its movement. In addition, other sensors onboard the GOES satellites are able to detect temperature variations across the United States. With the measurement of the temperature variations, NOAA is able to accurately create short-term temperature forecasts (NOAA-GOES). However, the limitations of the benefits provided by these sensors onboard the GOES satellites, have yet to be reached. As improvements in sensor design are developed, better monitoring of severe weather and more accurate temperature forecasts are possible. It has been suggested that improvements in the capabilities of the GOES satellites could lead to substantial improvements in daily commerce throughout the United States.

In response to the potential improvements to commerce provided by weather prediction, NOAA is planning the development of its next generation of weather satellites, the GOES-R series, which should be deployed starting in 2012. The key instruments in this new series of satellites are the Hyperspectral Environmental Sounder (HES) and the Advance Baseline Imager (ABI). The HES is expected to provide substantial improvements in the prediction of convective weather, such as thunder storms. The combination of the ABI and HES is expected to lead to an overall reduction in the variance and error in short term (3-hr) temperature forecasts throughout the United States.

Based on the procurement process of the U.S government, NOAA purchases its satellites in series. Each satellite in a series is essentially identical to all other satellites in that series. Thus, the value provided by each satellite in a series is unchanged. The only way to increase the value provide by a satellite is to procure a new series of satellites.

But, as new technologies are developed, greater value could be delivered to NOAA if a serviceable satellite was procured instead of a series of satellites. The increase in capability (unit-value increase) provided by the new instruments is described in a NOAA cost benefit analysis study and is fixed. It was assumed that only one HES and one ABI are needed on a target satellite or replacement satellite. The purpose of this example is to determine the additional value provided to NOAA by the early deployment of the ABI and HES through upgrades instead of waiting until the deployment of the GOES-R series.

6.1.1. Objective

If NOAA adopted a serviceable satellite design over the traditional satellite design, NOAA would have been able to deploy the new ABI and HES as the instruments become available instead of waiting until the next procurement period. Early deployment of the ABI and HES would have allowed for better weather prediction capabilities earlier, which would have provided benefit to the public earlier than would have been accomplished with the current deployment approach. Thus, the purpose of this example is the following:

- Determine the range of servicing prices below which NOAA would have chosen to upgrade the GOES satellites (assuming that the satellites were designed to be serviced).

- Based on the range of the servicing prices, determine the maximum servicing price below which NOAA would have originally designed the current series of GOES satellites to be serviceable.

- Through sensitivity analysis, determine the characteristics of the feasible non-commercial asset augmentation.

- Compare the characteristics of a feasible OOS market found in the commercial service case with those found in the non-commercial case. Determine the differences, if any, between commercial and non-commercial OOS and make general conclusions about the feasibility of asset augmentation.

6.2. Model Assumption and Characteristics

The GOES satellite system consists of two operational satellites at any given point in time. In order to provide constant observation of the continental United States, one satellite is positioned over the East coast and one satellite is positioned over the West coast. The current deployment process for satellite systems requires that the satellite have an operational life of about five years. As a result, every four years a new satellite is deployed in order to replace an older satellite. The deployment of these satellites is staggered by three years and alternates between the East and West coast locations. When the new GOES-R series of satellites are developed, NOAA anticipates that these satellites will have a longer lifetime. The deployment of the new series will shift from once every three years to once every five to seven years. See Figure 6–1 for NOAA's planned launch and deployment process. See Table 6-1 for definition and values of terms used in this example.

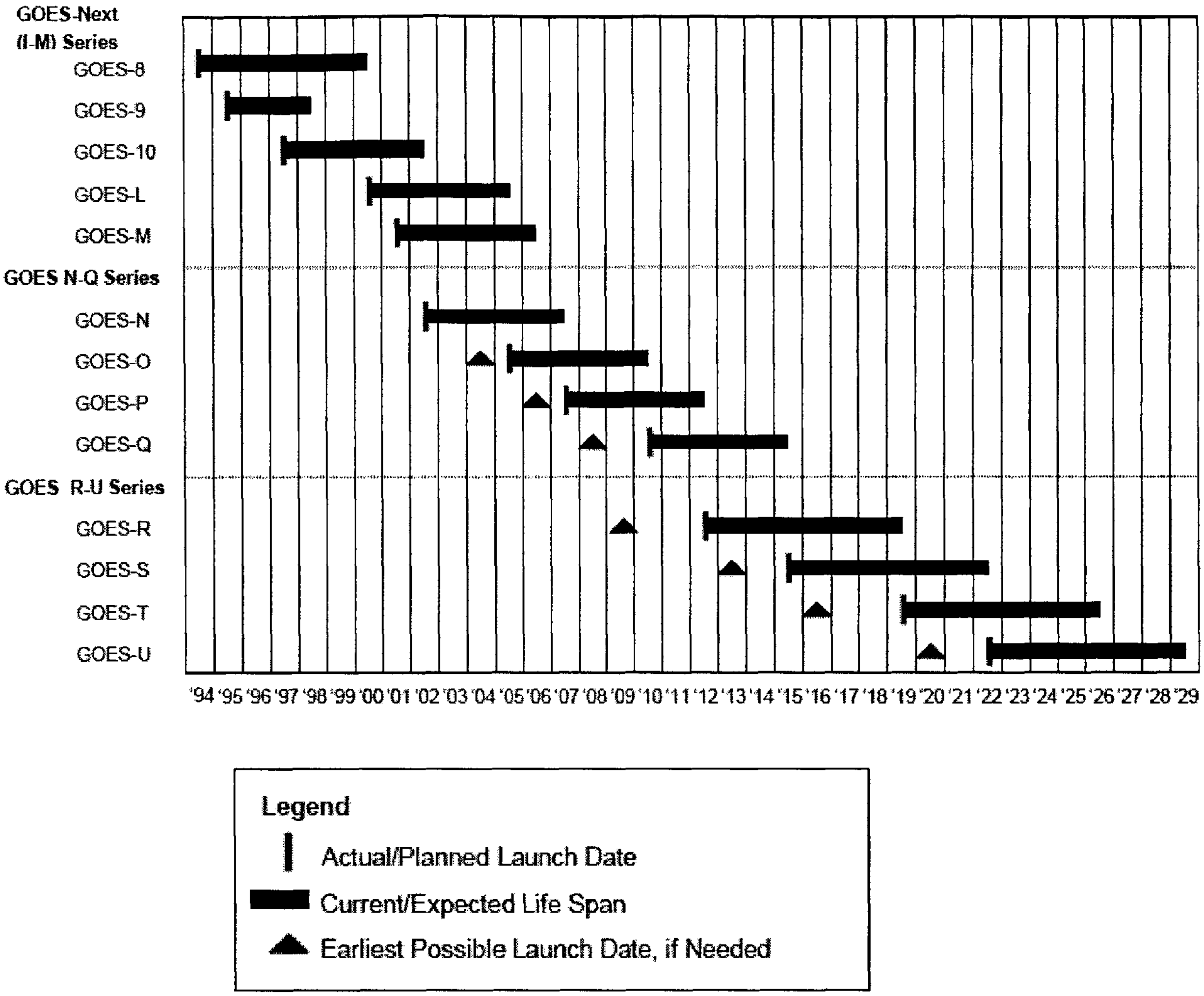


Figure 6–1: Procurement and Launch Schedule for the GOES Satellites (GAO, 2000)

Table 6-1: GOES Satellite Characteristics

Characteristic	Value
Start Time	2002
Stop Time	2028
GOES R/Replacement satellite cost	$90M (FY 2002), 7yr expected life, except for the 1st GOES-R
GOES – R Planned Launch	2012
GOES –R Instruments (HES and ABI)	$157.522M (NOAA, 2005)
GOES N & O Satellites	$123.5M each (FY 2002),5yr expected life (NOAA, 1998)
GOES P	$101.5M (FY 1998), 5yr expected life(NOAA, 1998)
GOES Q	$94.8M (FY 1998), 5yr expected life(NOAA, 1998)
GOES N Launch Date	4/2002 (GOES, 1998)
GOES O Launch Date	4/2005 (GOES, 1998)
GOES P Launch Date	4/2007 (GOES, 1998)
GOES Q Launch Date	4/2010 (GOES, 1998)
Launch Costs	$105.6M (FY 2002)
Total Airline Delays due to Weather (TDw)	Underlying Market
Airline Delays due to Convective weather (PD_{CWX})	50% (NOAA/DOC, 2002)
Percentage delays impacting U.S carriers (PD_{US})	75% (NOAA/DOC, 2002)
Percentage delays avoided due to reduced watch area (PD_{RWA})	20% (NOAA/DOC, 2002)
Percentage of delays avoided due to advance sounder (PD_{AS})	50% (NOAA/DOC, 2002)
Average delay time	3/4 hr (NOAA/DOC, 2002)
Weighted average operations cost	$3,055 / hr (FY 2002) (NOAA/DOC, 2002)
Value of passenger time	$30.44 / hr (FY 2002) (NOAA/DOC, 2002)
Average number of commercial passenger per flight	115 (NOAA/DOC, 2002)
Cost per ¾ delay (C_{PD})	$2291 (NOAA/DOC, 2002)
Temperature forecast error -Percent of load forecast error (TF_{ERR})	40% (NOAA/DOC, 2002)
Temperature error reduction for 3-hr forecasts (E_{RED})	25% (NOAA/DOC, 2002)
Average load forecast error (E_{TOT})	2.6% (NOAA/DOC, 2002)
Total Production (T_{PROD}) [MWH]	3,413,000,000 (NOAA/DOC, 2002)
Cost of Service per MWH (C_{SER})	Underlying Market

6.2.1. Baseline Strategy

The baseline strategy is defined by the 1997 GOES procurement plan. The first satellite, GOES–N, was launched in 2002, followed by GOES-O in 2005, GOES-P in 2007, and GOES-Q in 2010. The new GOES-R series, with the new ABI and HES, will begin deployment in 2012. The next series of GOES satellites is not anticipated until some time after 2028.

6.2.2. Uncertainties

The model looked at five future uncertainties. The first uncertainty is market uncertainty. Because the model examines the benefits of two industries, two market uncertainties must be developed. The third uncertainty is the uncertainty about the development of the new GOES-R series of satellites. Due the nature of the design of the GOES satellites, only one ABI and one HES will be required on a given satellite. As a result, there is no ability to increase satellite performance by a unit-increase, as was seen in the GEO communications example. The only benefit of the new GOES-R satellite is a reduction in satellite cost. The final two uncertainties in the model deal with the uncertainty around the readiness of the ABI and HES instruments.

As in Chapter 5, it was assumed that the readiness of the HES is independent of the readiness of the ABI and that the customer cannot effect the development of either technology. As before, the probability associated with the readiness of both technologies was modeled with an exponential distribution. A technology freeze of three years was assumed, thereby delaying any decision to upgrade until the fourth operational year.

6.2.3. Market Uncertainties

In the first two examples, customer value was a function of the uncertainty in a single underlying market. In this example, there are two underlying markets, which represent the two beneficiaries of the satellites: the airline industry and the electric companies. A pseudo-market of airline delays due to convective weather was modeled after historical data obtained from the U.S. Department of Transportation. (DOT Stats) The market for airline delays was modeled as a log-normal binomial tree distribution; thus the number of airline delays was bounded between zero and infinity. While a zero or infinite number of airline delays is not realistic, these values for the number of airline delays are not outside of the realm of possibility. One additional benefit of using the log-normal distribution is that it is consistent with the expectation that the difficultly in achieving an incremental reduction in airline delays will increase as the number of airline delays decreases; thus the chance of eliminating all airline delays due to convective weather is extremely small.

The initial market value was assumed to have 113,000 delays per year, an annual market drift of 0%, and annual market volatility of 25%.

For the electricity market, the market was modeled as the change in price for a Mega-watt hour (MWhr) of electricity. The uncertainty was modeled using historical data from the U.S. Department of Energy (DOE Stats). Again, the market was modeled using a log-normal binomial tree distribution because the log-normal distribution provides a realistic estimate for the change in price of a commercial investment. The initial market price for a Mega-Watt Hr of electricity was set at $41.3/MWhr, the drift in the price was set at 0% per year, and the volatility in the price was 2.5% per year. Finally, a constant demand of 3,413,000,000 MWhr/yr of electricity was assumed over the operational life of the satellite.

6.2.4. Time Horizon

The time horizon was set at the time of the expected development of the replacement series of satellites for the GOES-R series; i.e. the end-of-life of the fourth GOES-R satellite (2028). Because deployment strategies can vary over a fixed time horizon, any additional satellites, other than the planned satellites, that are needed to fill any remaining time in the time horizon were modeled after the fourth GOES-R satellite. Thus, if a strategy calls for the early deployment of the GOES-R series in 2008, the expected end of life of the fourth GOES-R satellite would be 2024. Under these conditions the time horizon would be filled with the deployment of a fifth R-Series satellite, which would be modeled after the fourth GOES-R satellite.

6.2.5. Decision Points

The decision points were chosen in the same way as they were for the commercial augmentation example. A satellite operator is given a single choice to service. The choice is varied annually between the earliest readiness of the ABI and HES (year four of the analysis period) and ends at the planned deployment of the GOES-R series of satellites (2012). The decision point for the GOES augmentation case are therefore 2006, 2007, 2008 … 2011.

6.2.6. Operational States

The operational states of the GOES system are similar to that of the GEO communications example with one exception. In the case of the GOES system, a satellite operator has the choice of either an ABI upgrade or an HES and ABI upgrade. The GOES-R series does not allow for an additional imaging instrument; therefore, the option for the launch of a more powerful satellite that was seen in the GEO communications example is not an option in the current example. The states of the system therefore reflect only the possible upgraded states of the satellite or the replacement of the system with the GOES-R series. The operational states of the GOES system are: Normal Operation (GOES-N), Normal Operation (Serviceable GOES-N), Upgraded Operation (ABI), Upgraded Operation (ABI & HES), and Replacement Operation (GOES-R).

- *Normal Operation (GOES-N)* – Normal operation of the initial GOES-N series satellite follows the baseline strategy. The satellite is operated as normal, the additional value provided by the satellite is zero and the only satellite costs are the operational costs.

- *Normal Operation (Serviceable GOES-N)* - Normal operation of a serviceable GOES-N satellite is identical to that of the normal operation of the initial GOES-N, except for one difference. The serviceable GOES-N satellite has the additional initial development cost associated with the serviceable satellite design.

- *Upgraded Operation (ABI)* – The upgraded ABI operational state is the state where the serviceable GOES-N satellite has been upgraded with the new ABI instrument. As a result, the additional value of the satellite is the savings that occurs from only the ABI. The ABI creates savings for the Airline industry due to the decrease in convective weather delays. In order to reach the upgraded ABI state, a satellite must be in the Normal Operation (serviceable GOES-N) state and the satellite operator must spend the additional cost associated with servicing and procurement of the ABI imager.

- *Upgraded Operation (ABI & HES)* – The upgrade ABI & HES operational state is the state where the serviceable GOES-N satellite has been upgraded with the new ABI and HES instruments. As a result, the additional value of the satellite is the savings that occurs from both the ABI and HES. In addition to the savings for the airlines generated by the ABI, the HES provides savings to the electricity industry due to the decrease in overproduction of electricity. In order to reach the upgraded ABI & HES state, a satellite must be in either the "Normal Operation (serviceable GOES-N)" state or the "Upgraded Operation (ABI)" state. To enter the "Upgraded Operation (ABI & HES)", the satellite operator must spend the additional cost associated with servicing and procurement of the either just the HES or the ABI & HES.

- *Replacement Operation (GOES-R)* - Replacement operation of the GOES-R series satellite follows the normal operation of the GOES-N satellites except that the GOES-R series has the additional value provided by the savings created by the new ABI and HES instruments along with the reduced cost of satellite deployment. To switch to this operational state, the satellite can be in any one of the other operational states. The operator must spend the cost associated with procurement as well as the cost of development of the new instruments.

6.2.7. Risk

In the event that a servicer caused a satellite failure, the satellite operator would incur a loss equal to the amount of the expected future savings. Once again risk is viewed as a probabilistic reduction in value associated with the risk of satellite failure.

6.2.8. Benefit Function

In a cost benefit analysis developed for the Department of Commerce, NOAA experts state that the new GOES instruments will provide benefit to at least eight areas of industry. The two areas that this study addresses are the aviation industry and the electric power industry. Everyday the Federal Aviation Administration (FAA) and the airlines collaborate to set and modify flight plans to ensure that flights depart and arrive on schedule. Severe weather proves to be the major deterrent to maintaining the airline schedules. Today, the best available weather forecasting product, the collaborative convective forecast product, shows a large box within which storms have a probability of occurring. This box typically comprises an area of about 10,000 to 30,000 square miles. According to industry and scientific experts, the GOES HES will provide forecasting that can predict convective weather one to two hours in advance. The result of this improvement will be a significant reduction in the severe weather watch area that results in savings for the airline industry (NOAA/DOC, 2002). The costs savings that could be provided to the airline industry due to augmenting the current GOES satellite with the new HES is described by Equation 6-1.

Equation 6-1$^{\text{(NOAA/DOC, 2002)}}$

$$\text{Savings}_{\text{Airline}} = (TD_W)(PD_{CWX})(PD_{US})(PD_{RWA})(PD_{AS})(C_{PD})$$

Another beneficiary of the GOES instrument upgrades is the electric power industry. Electricity cannot be economically stored and production is essentially consumed instantaneously. Power fluctuations throughout the day in response to temperature changes create power demands that often require last minute decisions to buy or sell power and/or start expensive gas-fired "peaking units." Operators typically recompute load productions every two-hours around the clock using updated weather forecasts. With huge amounts of electricity being produced each day, electric utility companies have a great desire to reduce the over production of electricity. Currently, electric utility load forecasts are off by approximately 2.6 percent on average. Experts predict that the implementation of the GOES HES and ABI will decrease power production error by 0.26 percent, reducing the total average error in power production to 2.34% (NOAA/DOC, 2002). The resulting cost savings for the electric power industry as a result of augmenting the current GEOS satellites with a new HES and ABI is described by Equation 6-2.

Equation 6-2 (NOAA/DOC, 2002)

$$\text{Savings}_{\text{Power}} = (TF_{ERR})(E_{RED})(E_{TOT})(T_{PROD})(C_{SER})$$

The total benefit provided by augmenting the GOES satellite with new payloads includes the savings for both the airline and electric power industries. However, the costs savings for the industries are separate from the costs associated with the GOES satellites. It was assumed that because NOAA is a government agency that its purpose was to support the U.S. public. Thus, the relationship between the cost savings for industry and the cost of the GOES satellites was assumed to be 1:1. As a result of this assumption, the value delivered from the upgrades is the sum of the cost savings from the airline and electric power industries less the cost of operation, development, and servicing of the GOES satellite system.

Equation 6-3

$$EB_{T_K} = Savings_{Power} + Savings_{Airlines}$$

6.2.9. Costs

The matrix for the switching costs between operational states of the system is given below in Table 6-2. Normal Operation (GOES-R) was not included in the first column of the matrix because this state only represents an end-state of the system. The annual operating costs were assumed to be 10% of the procurement cost of the satellite.

Table 6-2: Switching Cost between the Operational States of the GOES System

	Normal Operation (GOES-N)	Normal Operation (Serviceable GOES-N)	Upgraded Operation (ABI)	Upgraded Operation (ABI & HES)	Replacement Operation (GOES-R)
Normal Operation (GOES-N)	0	Infinity	Infinity	Infinity	Cost of GOES-R
Normal Operation (Serviceable GOES-N)	Infinity	0	Servicing Price + price of ABI	Servicing Price + price of ABI and HES	Cost of GOES-R
Upgraded Operation (ABI)	Infinity	Infinity	0	Servicing Price + price of HES	Cost of GOES-R
Upgraded Operation (ABI & HES)	Infinity	Infinity	Infinity	0	Cost of GOES-R

6.2.10. Value Function

In this example, the value delivered from the upgrades is the sum of the cost savings from the airline and electric power industries less the cost of operation, development, and servicing of the GOES satellite system. The equation for the expected value at any point in time is therefore:

Equation 6-4

$$
\begin{aligned}
EV_{[T_{n-1},T_n]}^{S_i-S_f} = {} & EB_{[T_{n-1},T_n]}^{S_1}(X_i)_{T_{n-1}} \\
& + e^{-\Re_{IRR}(T_n-T_{n-1})}\left[p\left(EV_{[T_n]}^{S_{n1}}(X_{i+1})_{T_n}\right)+(1-p)\left(EV_{[T_n]}^{S_{n1}}(X_{i-1})_{T_n}\right)\right] \\
& -(Cop)_{[T_{n-1},T_n]}-(C_{switch})_{T_{n-1}}^{S_i-S_f}
\end{aligned}
$$

6.2.11. Utility Function

Developing a utility function for the decision-maker (NOAA) is difficult because the decision-maker is not the benefactor of the servicing. NOAA provides the resources and capital investment that delivers the weather prediction capability and the airline industry and power production industry reap the benefits. Based on the division of the benefits and costs between three different entities, it was assumed that NOAA would expect that, for each dollar it spends, at least one dollar will be delivered to the benefactor of the weather system. Based on this assumption, the utility function for NOAA was modeled using a "risk-neutral" (expected value) risk preference. There may be some debate about this assumption, but it was not the intention of this thesis to suggest how the U.S government should evaluate its expenses. The "risk-neutral" utility function assumption allows for the effect of the decision-maker's risk preference to be removed from the calculation of value (i.e. the customer's utility function (U) is simply a scalar multiplier), thus it does not change the customer's perception of risk and rewards.

6.3. Sample Results

Figure 6–2 illustrates the results for one feasible case of servicing the GOES system. In the GOES case, the customer has the potential for two upgrades; the sounder or the sounder and imager. The servicing cost penalty below which the two upgrades provide the most value to the customer can be determined from Figure 6–2. The lighter shaded region represents the feasible range of servicing prices for the combination of the imager and sounder upgrade. The darker shaded region represents the range of servicing prices for only the sounder upgrade. The servicing cost penalty represents the difference in program costs between the serviceable strategy and the current GOES procurement and development strategy. P(HES) represents the cumulative probability of the readiness of the HES, and P(ABI) represents the cumulative probability of the readiness of the ABI. P(New Sat) represents the cumulative probability about the readiness of the GOES-R series. Note that, while the new series of satellites cannot include additional value-generating units, the GOES-R series is are expected to cost less to develop. Therefore, it is assumed that the development of new satellite bus technology is used to reduce the cost of satellite procurement.

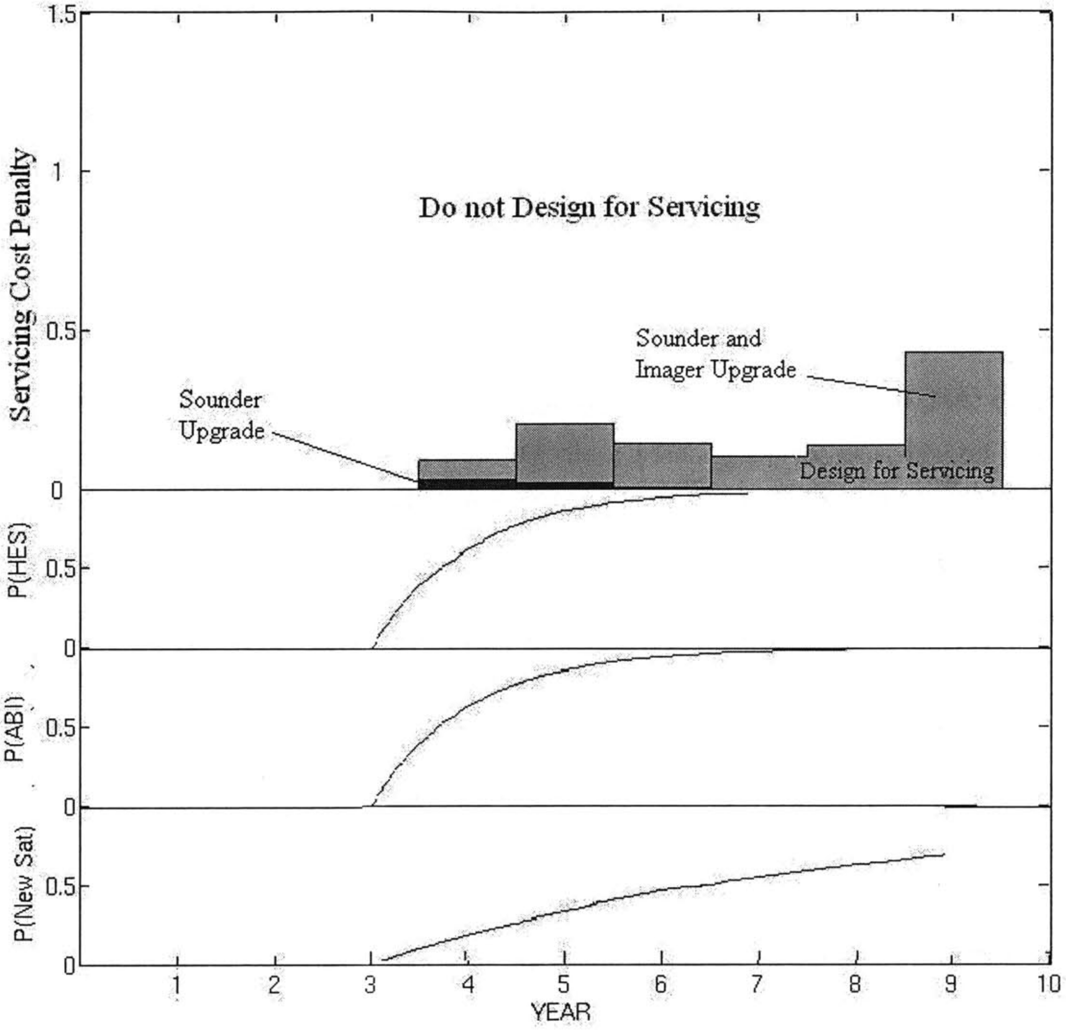


Figure 6–2: Sample GOES Results

The extent of the feasible servicing region in Figure 6–2 indicates that the combination of the imager and sounder upgrade provides significantly more value to the customer than the sounder upgrade alone. The reason for this large difference is that the combination upgrade creates benefits for both the airline and electricity markets, while the sounder upgrade only provides savings to the airline industry. The sensitivity of these results to changes in the model parameters was examined to determine if the sensitivities of the non-commercial satellite example are the same as those found for the commercial satellite example.

6.3.1. Sensitivity to New Technology Improvement

Since only a single data point for the benefits of the new sounder and imager could be found, there was not enough data to predict the effect that varying levels of technology improvement would have on the customer's maximum servicing price.

6.3.2. Sensitivity to Airline Volatility

Figure 6–3 shows the results of varying the volatility associated with airline delays. The volatility of the airline market was varied in 15% increments between 15%, 30%, 45%, 60% and 75%. The volatility of the electricity market was fixed at the historical value of 2.5%. From the airline sensitivity analysis, there is no change in the customer's maximum servicing price for either upgrade. The results for the different volatility values are so similar that they cannot be distinguished on the graph. The lack of any change due to varying market volatility is the result of the overwhelming savings provided by the combination upgrade. The combination upgrade contains the savings for both the airline and electricity market. Therefore, the option for the combination upgrade will always provide more value over the option for only the sounder upgrade regardless of the level of volatility in the airline market. Thus, when multiple forms of augmentation exist, a customer should focus his decision to service on upgrades that are not common among multiple augmentations options.

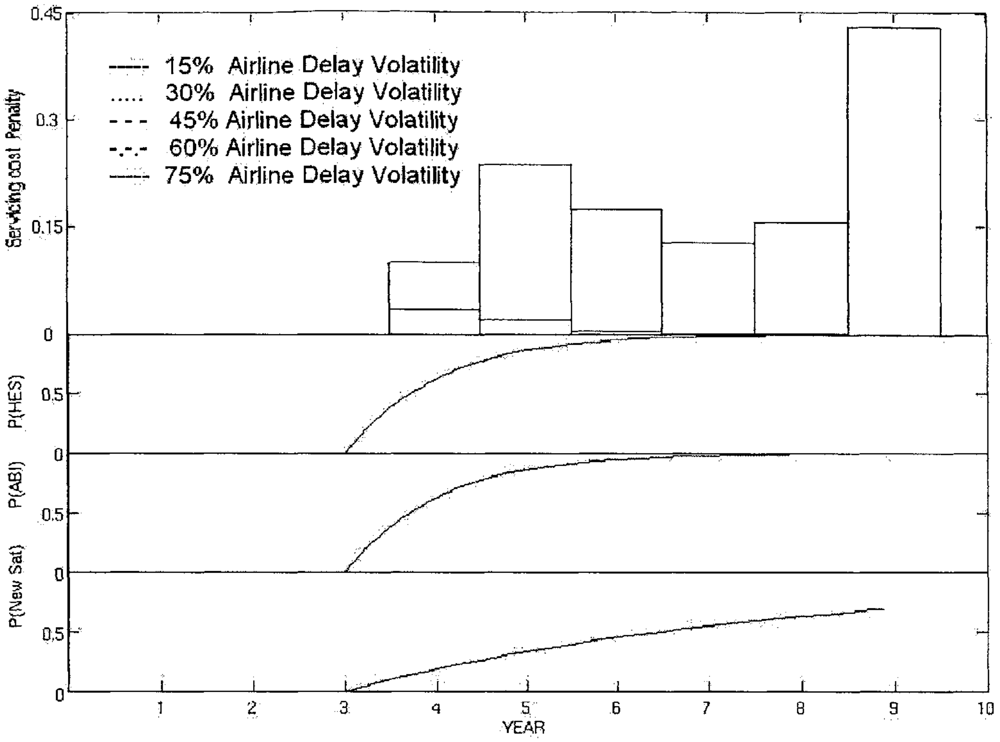


Figure 6–3: Varying Airline Volatility

6.3.3. Sensitivity to Electricity Volatility

Figure 6–4 shows the results of varying the volatility of electricity prices on the maximum servicing price. Although the electricity market has a historically low volatility of 2.5%, the volatility of the electricity market was varied to examine its effect on the customer's maximum servicing price. The volatility of electricity prices was varied between 10%, 30%, 50%, and 70%. The volatility of the pseudo-airline market was fixed at the historical value of 25%.

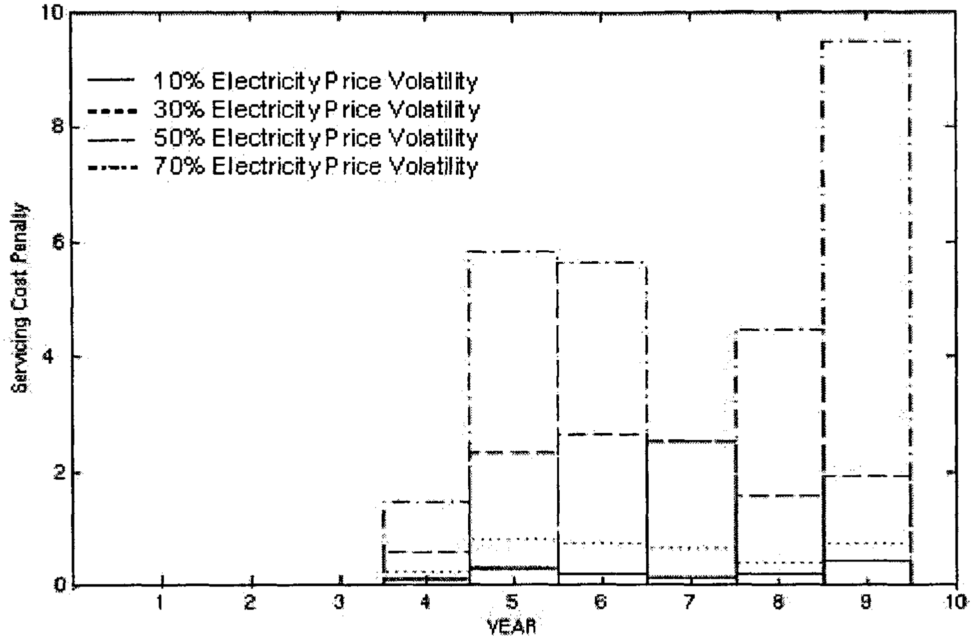


Figure 6–4: Varying Electricity Volatility

From the sensitivity analysis around the price of electricity, there appears to be significant change in the customer's maximum servicing price. It is apparent that, as the volatility in the price of electricity increases, the customer has the potential to gain more value, making highly volatile markets more favorable. This appears to be in direct contradiction with the finding for the previous examples that highly volatile markets are not favorable servicing markets. In the commercial satellite upgrade example, a highly volatile market made it more attractive to pursue more valuable strategies, thus decreasing the attraction of servicing. In this case, however, the customer is fixed to only unit-value increases. Due to the constraints on the design, the customer is prevented from putting up more value-generating units. The result is that servicing will always be the most beneficial option because it allows for the earlier deployment of new technology. Thus, servicing makes sense in highly volatile markets when the option to service always provides more value over alternative options. Therefore, in situations where a customer only has the option to service (i.e. replacement is not an option) or replacement would not result in a more capable satellite, servicing will be the best choice for the decision maker no matter the volatility of the market. This finding supports past work that has shown that the more volatile the market, the more value servicing delivers to the customer (Lamassoure, 2001), (Saleh, 2002).

6.3.4. *Sensitivity to Servicer Risk*

Figure 6–5 shows the results of varying the risk of failure associated with servicing. As before, the servicer risk was varied between 0%, 5%, 10%, and 15%. From the sensitivity analysis for the servicer risk, the same behavior is seen as was seen in the commercial satellite upgrade example. When the servicer risk is increased, the customer's maximum servicing price decreases fairly uniformly with respect to time, thus making servicing less attractive.

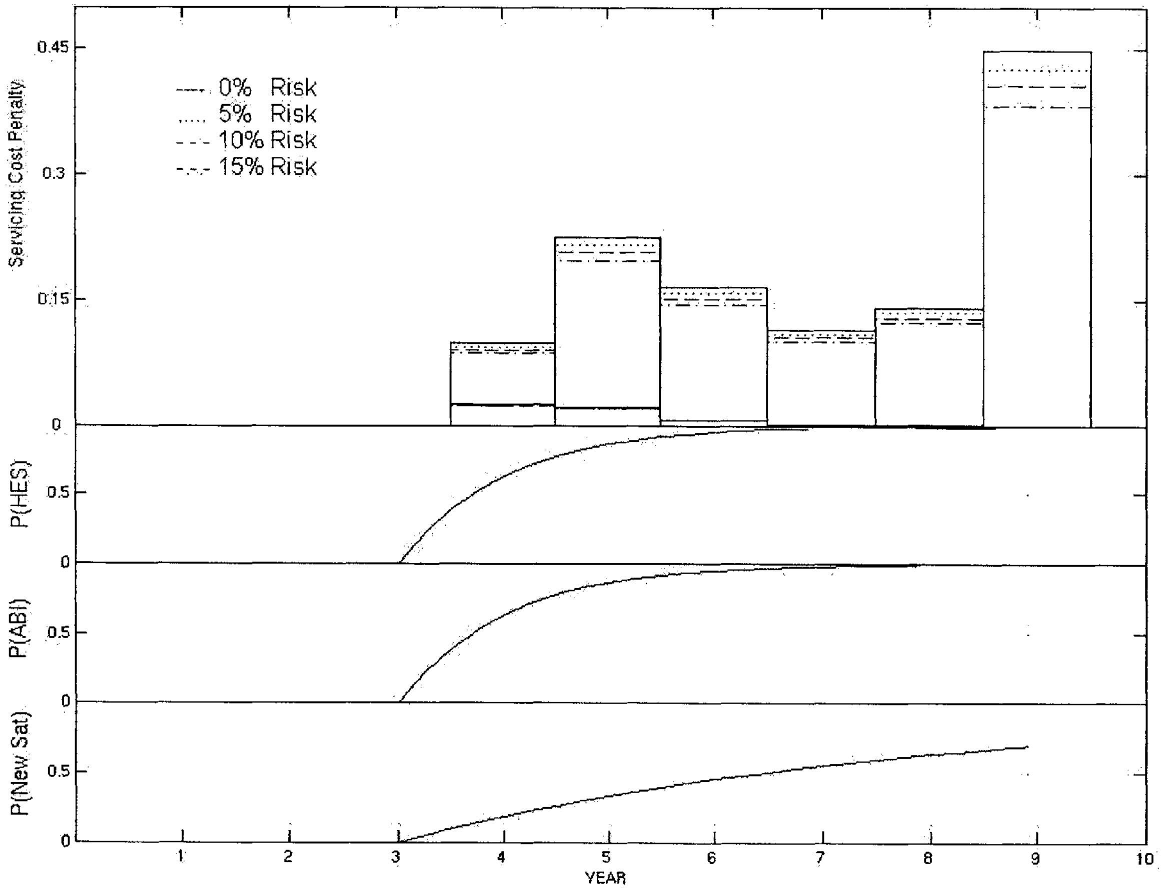


Figure 6–5: Varying Servicer Risk

6.3.5. Sensitivity to Risk Preference

Since the decision maker and the benefactor are different entities in the GOES satellite example, it is assumed that a decision maker will make the servicing decision on a risk-neutral (expected value) basis. No assumption about the decision process of a government agency is made with regard to its effect on commerce. As a result, risk-preference evaluation was not performed.

6.3.6. Sensitivity to Expected Availability of Sounder

The unique nature of the GOES case is the option to perform one or two upgrades. However, the ability to perform these upgrades depends on the availability of new technologies. In the case of servicing the airline market, the only required technology is the sounder. However to serve the electricity market, both the imager and sounder must be developed. The interplay between the uncertainties of these two technologies produces some interesting results.

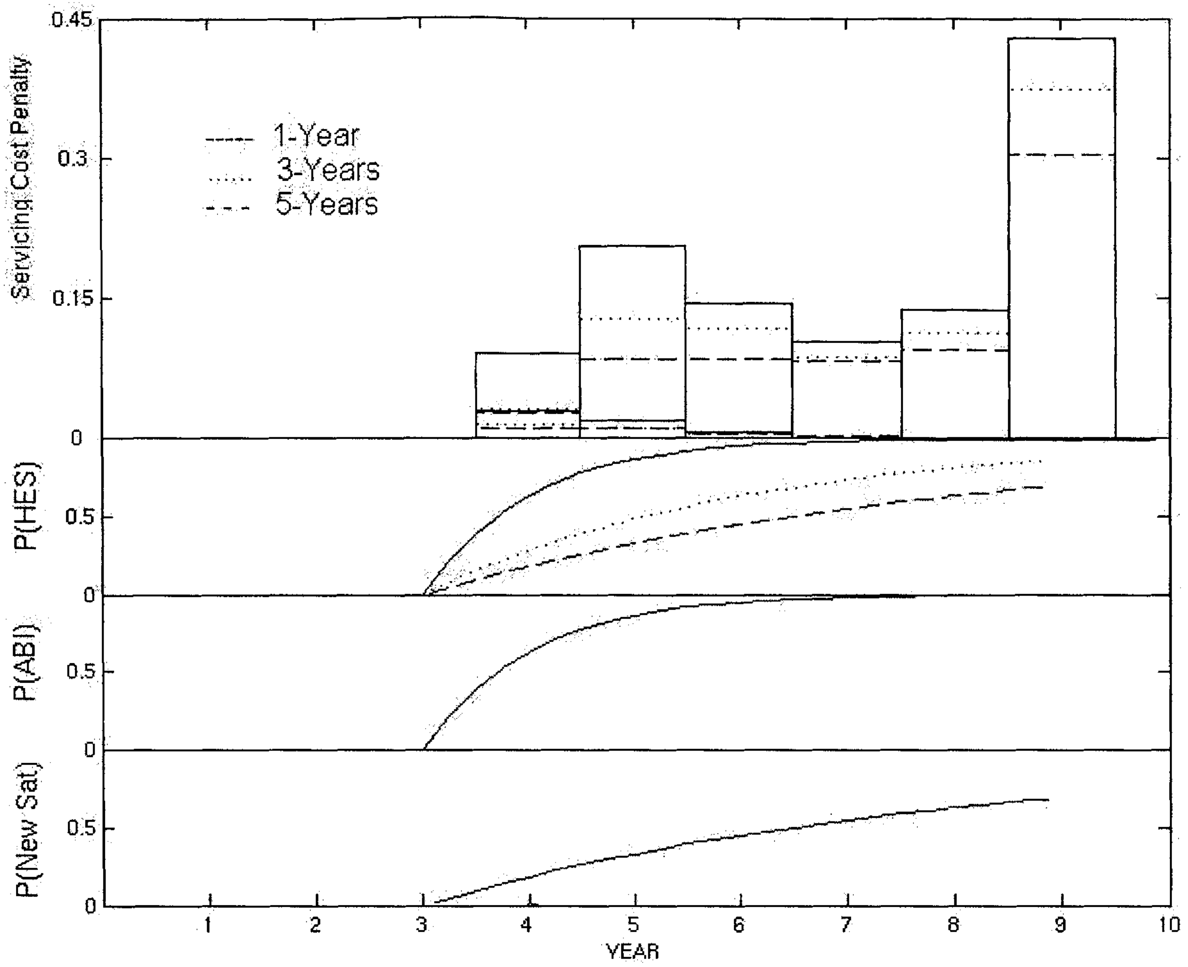


Figure 6–6: Varying Expected Availability of Sounder

Figure 6–6 shows the result of a sensitivity analysis around the readiness of the new sounder technology. In this case, the mean availability of the imager was fixed at one year, while the mean availability of the sounder was varied between one, three, and five years. As can be seen, the longer it takes for the sounder to be developed, the lower the expected value for both levels of upgrade. The reason for this effect is that neither form of servicing can take place without the development of the HES. The longer the HES takes to develop, the longer one has to wait for the development of this payload and the lower the cost savings for the airline and electric power industries. Therefore, technologies that play essential roles in multiple forms of servicing become a potential bottle-neck in the upgrade of the customer's satellite. To increase the likelihood of servicing, emphasis should be placed on reducing any uncertainty in the development of payloads that are essential to multiple forms of upgrade.

6.3.7. Sensitivity to Expected Availability of the Imager

Figure 6–7 summarizes the results for the sensitivity analysis of the readiness of the imager. Here the mean availability of the sounder was fixed at one year, while the mean availability for the imager was varied between one, three, and five years. The figure indicates that, the longer the imager takes to develop, the less valuable the option. However, the figure also shows that the maximum servicing price for upgrading of just the sounder increases over time. This does not mean that the airline industry receives more value from the upgrade. The increase in maximum servicing price is the result of the uncertainty in the readiness of the imager. This uncertainty results in an increase in the likelihood that a customer would spend more on the upgrade of the sounder. Since there can be substantial uncertainty about the readiness of the imager, the customer's optimal strategy becomes the choice to upgrade only the sounder. The effect of the uncertainty in the imager readiness reinforces the previous finding that uncertainties in the occurrence of essential technology should be reduced in order to maximize customer value.

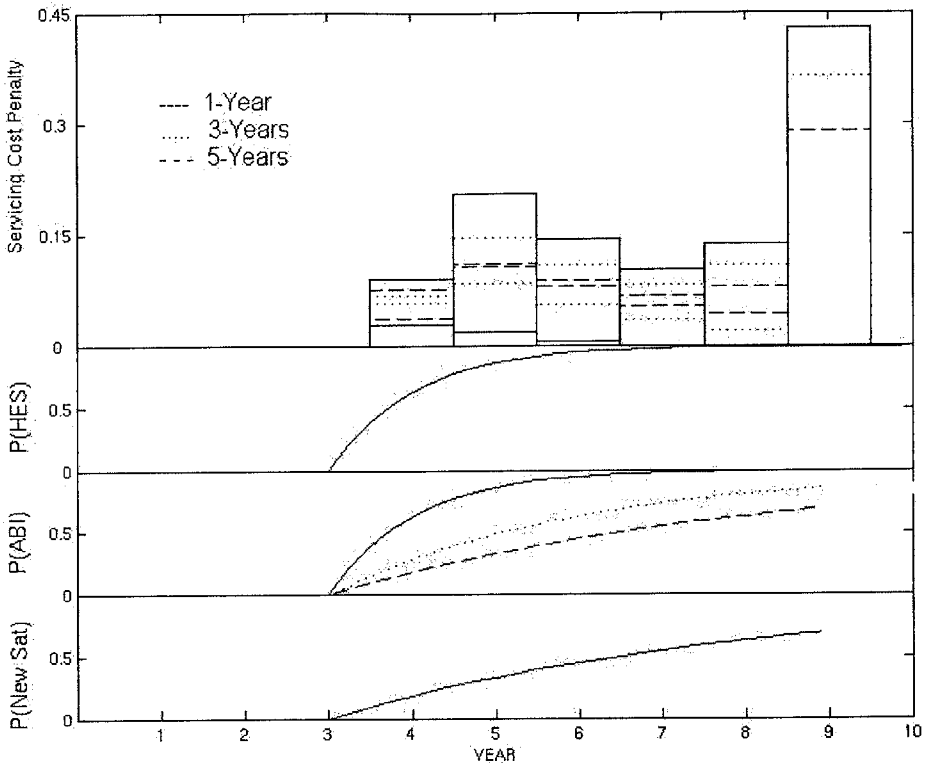


Figure 6–7: Varying Expected Availability of Imager

6.4. Conclusions

Overall, the findings for the non-commercial case are consistent with those of the commercial case with only two exceptions. The two new findings that resulted from the non-commercial case are: 1) highly volatile markets produce favorable servicing markets if servicing is always the most beneficial option and 2) emphasis should be placed on reducing uncertainty around the readiness of technologies that play critical roles in various upgrade options. Through the examination of both asset augmentation cases, it was found that satellite upgrades continue to provide additional value over traditional satellite design. Thus, regardless of the type of customer, the design of a serviceable satellite provides a satellite operator with the flexibility to react to future uncertainty that traditional satellite design does not offer. From this flexibility, satellite operators are able to create additional value that could not be captured with traditional design.

If only for the purpose of satellite upgrade, OOS appears to provide a needed change for the satellite industry. The change consists of new satellite designs that promote flexibility as opposed to traditional satellite designs that are completely inflexible with respect to future uncertainty. By adopting the idea of OOS, the aerospace industry can grasp the concept of generating value out of uncertainty that has eluded the industry since its creation.

Now that the characteristics of a feasible OOS market have been determined, methods for meeting the customer's need for this value must be identified. The next chapter examines the other side of the commercial servicing market—the provider side. By utilizing the characteristics of a feasible OOS market found in the last three chapters, the service provider can determine which form of servicing promotes the largest range of servicing prices. The largest range of servicing prices will result in the most favorable market of OOS for both the customer and provider.

Chapter 7. Provider Side of On-Orbit Servicing

The next step in the framework for the evaluation OOS is to determine the provider's minimum servicing price. After determining when the customer's value delivered by servicing is zero and the associated maximum servicing price, the next step is to examine how the provider will deliver value to the customer. Recall, that the provider is concerned with fulfilling one or more of the customer's fundamental functions of servicing (asset assessment, re-organization, restoration, or augmentation). The fundamental functions are unique to the customer and provide no information concerning how a service provider will provide the functions. Thus the service provider must develop an understanding of the relationship between the customer's functions of servicing and the provider's forms of servicing.

The previous three chapters examined the customer's side of OOS. These chapters focused on determining the additional value that OOS provided and from that value determined the maximum servicing price. This chapter will give a brief description of how to examine the provider's side of OOS. Six forms of servicing are introduced as ways in which OOS can provide value to the customer through meeting customer need. Through the description of these forms of servicing, it will be discussed how different forms of servicing map to customer needs. In the end, the provider should be able to determine a servicer design that meets customer needs and the minimum servicing price associated with that design. Due to the complex nature of the provider side of the market, the provider side of the OOS market is being left for future research. Thus the discussion in this chapter is conceptual. The purpose of this chapter is to provide an introduction to how the various forms of servicing map to the fundamental functions of servicing.

7.1. Understanding the Provider's Perspective

A provider can select different architectural forms of servicing with which to meet the customer's needs. Another way to look at this is that multiple service providers exist each with their own different forms of servicing. Each form of servicing has a minimum price at or above the price that a provider must charge for servicing. To determine if a form of servicing meets a customer's need, the provider must compare the minimum price of servicing for his form of servicing with the customer's maximum servicing price. If the minimum servicing price is greater than the maximum servicing price, the provider's form cannot deliver the required value to the customer. If the minimum servicing for the provider's form is at or below the maximum servicing price, the provider's form is capable of delivering the required value (or more) to the customer.

7.2. On-Orbit Servicing Forms

Before getting into the specifics of determining the minimum servicing price, there is a need to discuss the different forms of OOS available to the OOS provider. Kreisel suggests that there are three distinctive classes of OOS: motion, manipulation, and observation (Kreisel, 2005). While these classes of OOS capture the general aspects of a provider design, they do not provide enough distinction to map customer function to provider form. To gain a better distinction among the forms of servicing, Kreisel's "manipulation" and "motion" can be broken down into more distinct forms of servicing. By breaking down Kreisel's classes of servicing, servicing is categorized into the following six forms of on-orbit servicing: inspection, refueling, relocation, recovery, repair, and upgrade.

7.2.1. Inspection

Inspection is the most basic form of OOS. Inspection is the visual observation of a satellite in orbit. By observing a satellite, a large number of satellite problems can be resolved. De Puetuer states that inspection is valuable in the case of a satellite that has a severe malfunction where close-up view of the satellite could help to clarify the problem. Diagnostic data derived from inspection can be a basis for recovery actions from the ground (De Peuter). The actual level of visual resolution can vary depending on the nature of the service.

For instance, on a macro-scale, inspection could be used to determine the physical state of the satellite. Inspection could be used to determine if an antenna or solar array has deployed, or inspection could be used to determine the existence of damage. On a micro-scale, inspection could be used to determine failure in satellite components or subsystems. Inspection could assist with mechanical problems that cannot be resolved from the ground. Finally inspection is required for rendezvous and docking of the servicer with the target satellite, a basic element of servicing. Because inspection of a satellite is incorporated into a large number of servicing missions, inspection is the building block of all other forms of service. As with all cases, inspection relates to fulfilling one of the fundamental functions of servicing. In this case the primary purpose of inspection is to provide information about the physical condition of a satellite; hence inspection fulfills the customer need for the fundamental form of asset assessment.

7.2.2. Refueling

Refueling is the case of on-orbit servicing where a servicer resupplies a target satellite with propellant. Additional propellant could be used to support maneuvers, orbit relocations, or station-keeping. In general, refueling supports two practical servicing scenarios:

1) Refueling can extend the life of a satellite that has reached the end of its operational life due to running out of propellant. Here the servicer could provide propellant that would be used for station-keeping, thus allowing the satellite to remain operational. By extending the satellite's operational life, refueling restores the satellite's value. As a result, refueling for the purpose of life extension fulfills a customer's need for asset restoration. This case would be identical to the life extension case discussed in Chapter 4.

2) By replenishing propellant before or after a maneuver, refueling can allow satellites to reposition themselves and maintain the operational life. In this case, maneuvering to a new orbit would be performed by the satellite without the help of the servicer. The servicer would either provide additional propellant to complete the maneuver or replenish the satellite's exhausted propellant after the maneuver was completed. By providing/restoring the operational life of the satellite, it may appear that refueling represents a form of asset restoration, but this is not the case. Refueling a satellite for the purpose of maneuvering provides the customer with one way to re-organize the asset(s). The operational life of the satellite is maintained, not extended. The purpose of refueling in this case is to move the satellite.

7.2.3. Relocation

Relocation is the form of servicing in which the purpose of servicing is to move the satellite from one orbit to another. Unlike refueling, relocation of a target satellite is accomplished by the servicer physically attaching itself to the target satellite. Relocations can be applied in three general cases: repositioning, decommissioning, and life extension. In the case of repositioning a satellite, relocation has the identical effect as refueling a satellite. However, the difference between refueling and relocation is that in the case of relocation the servicing satellite provides the maneuvering capability and the target satellite does not need to expend its own fuel. It is important to note that both refueling and relocation can satisfy the same customer need for re-organization, but in significantly different ways. Thus, a customer is given the choice of two forms of service that can fulfill the same need.

Another case of satellite relocation is the decommissioning of the target satellite. Decommissioning is currently the most practical application of relocation servicing. For decommissioning, the servicer places a target satellite into a graveyard orbit. Although decommissioning of a satellite does not allow for additional revenue to be generated, it provides a customer a way to prevent the loss of future revenue. For example, in 2004 the U.S. Federal Communications Commission (FCC) required that satellite operators guarantee the decommissioning of their GEO communications satellites (FCC, 2004). If an operator is unable to decommission the satellite, the operator takes on the risk of losing future FCC licenses. Thus, decommissioning provides security for the customer (satellite operator) by providing a means of guaranteeing future value. Decommissioning fulfills the customer need for asset restoration because decommissioning increases the customer's overall expected value by preventing loss of future revenues brought about by FCC mandates.

The last case of asset restoration consists of satellite decommissioning, but for a different purpose than was discussed above. In this case a satellite gains additional operational life by using the propellant it would have used for decommissioning to supplement propellant used for station-keeping. This allows a customer to extend the life of the satellite without the need for servicing, dependent however on the customer's ability to decommission the satellite in the future (through servicing). De Peuter believes that "a telecom satellite could continue operating until propellant depletion (roughly six months of extra exploitation)", and then have a servicer move the satellite into a graveyard orbit (De Peuter). Generally, a servicer that performs satellite relocation would provide the customer with the re-organization of assets, but relocation also opens the doors to other possibilities, such as life extension (asset restoration).

7.2.4. ***Recovery***

Recovery is the unique case of a servicer repositioning a target satellite into a new orbit in response to a maneuver or upper stage failure. This case differs from the refueling and relocation forms of servicing because in this case recovery of a satellite takes place before the satellite has become operational. Since the satellite is not operational before servicing takes place and the service aims at delivering the customer the expected value from the satellite, recovery restores a customer's assets.

7.2.5. ***Repair***

Repair is the case where a servicer rendezvouses with a target satellite and repairs a damaged or malfunctioning system. An example of a repair mission is physically deploying an antenna, solar array, or installing replacement components. A special form of repair is that of software upload. The remote upload of software to a target satellite is a case of satellite servicing where a servicer is not needed. Nilchiani points out that "remote software upgrades can help the system to maintain its functionality in an uncertain environment (Nilchiani and Hastings, 2004)." If software upload is a way in which to maintain satellite functionality, then it represents a form of satellite repair. Satellite uploading would require that a satellite designer design for this form of servicing. This would mean that software upload would be a two-part decision process. However, with today's current satellite design practices, satellites already have the inherent capability to be reprogrammed on-orbit. As a result, software uploading should be viewed as a form of servicing involving a one-part customer decision process. Repairing a customer's satellite is an example of restoring a customer's value by restoring the satellite to its expected state of operation.

7.2.6. Upgrade

Upgrade is the case in which a servicer rendezvouses with the target satellite and performs a service in which the capability of the satellite is changed, preferably increased. In this case, the replacement of the Hubble Space Telescope (HST) camera(s) is an example of upgrading. Replacing the HST cameras allows operators to look at additional parts of the visible spectrum, as well as to look deeper into the universe. The result is an increase in the value HST delivers to its operator. Software uploading also provides a unique opportunity for satellite upgrade. As in the case of satellite repair, software upgrading represents a form of servicing involving a one-part decision process. The purpose of software upgrade is to increase the value delivered to the customer through new software programs. Upgrade is a form of service that increases the capability of the customer's assets such that the asset provides additional value to the customer.

After a provider determines which form of servicing to employ, the provider must determine the minimum price of servicing associated with that design. The specifics of how to determine this price are unique to the provider. This price could be based on the customer's architecture, delivery method, company model, financing, etc. It is not the intention of this thesis to describe how a provider should design the servicing architecture. Therefore, it is assumed that a provider can determine his own minimum servicing price. Given that a provider has the minimum servicing price for his architecture, the next step is for the provider to determine if a market exists.

7.3. Mapping Customer Function to Provider Form

The previous section provided a discussion of the various forms of servicing and how they can be applied to meeting the customer's fundamental functions of servicing. Table 7-1 depicts the relationship between the customer's fundamental functions of servicing and the provider's architectural forms of servicing. Examination of the table shows that certain forms of servicing cannot meet a certain customer need. For example, a servicer design solely for inspection cannot perform asset re-organization, restoration, or augmentation. But a servicer that is designed for refueling or relocation can provide all functions of servicing except asset augmentation.

Table 7-1: Mapping Fundamental Functions of Servicing to the Architectural Forms of Servicing

	Fundamental functions of servicing							
	Asset Assessment		Asset Re-organization		Asset Restoration		Asset Augmentation	
Architectural forms of on-orbit servicing	Non-Serviceable	Serviceable	Non-Serviceable	Serviceable	Non-Serviceable	Serviceable	Non-Serviceable	Serviceable
Inspection	Visual	Visual	N/A	N/A	N/A	N/A	N/A	N/A
Refueling	Visual/ Physical	Visual/ Physical	N/A	Orbit Relocation	GEO Life Extension	Life Extension	N/A	N/A
Relocation	Visual/ Physical	Visual/ Physical	Space Tug	Orbit Relocation	GEO Life Extension	Decommission Life Extension	N/A	N/A
Recovery	Visual/ Physical	Visual/ Physical	N/A	N/A	N/A	Launch Failure	N/A	N/A
Repair	Visual/ Physical	Visual/ Physical	N/A	N/A	Software	Physical	N/A	N/A
Upgrade	Visual/ Physical	Visual/ Physical	N/A	N/A	N/A	N/A	Software	Physical

An implication of Table 7-1 is that a provider is capable of determining which servicer to design in order to meet a customer need. For example, if a customer needed orbit relocation and has designed a serviceable satellite, the customer is looking to fulfill the need for asset re-organization. A service provider could fulfill the customer's need by designing either a servicer capable of refueling or a servicer capable of relocation. Thus Table 7-1 provides a means of mapping the various forms of servicer design to the various fundamental functions of servicing associated with customer need.

7.4. Elements of the Provider's Point of View

Although this thesis does not detail the steps that are required for determining a provider's minimum servicing price, the aim of this section is provide an idea of some of the elements a service provider should take into consideration. Unlike the customer side of the market, the provider's minimum servicing price is a function of the form of servicing. Thus with each servicer design, representative of at least one form of servicing, comes a unique minimum servicing price. Each potential servicer design has many elements of its design that can define the minimum servicing price for that design. For instance, a servicer that could be used once would have a dramatically different minimum servicing price compared to a servicer that could service multiple satellites. Therefore, based on these design elements, it is assumed that a service provider can determine his own minimum servicing price based on his unique economic and technical choices. Below is a list of design elements that a service provider should consider when designing a satellite servicer.

7.4.1. Type of Servicer

The type of servicer that a provider might choose depends on the forms of servicing. Recall, there are six forms of servicing: inspection, refueling, relocation, recovery, repair, and upgrade. Based on a provider's choice, the design of a servicer could support multiple forms of servicing or only one form of servicing. For example, Orbital Recovery's ConeXpress is the case of a servicer designed to act as a space tug. Based on the design of ConeXpress, the only form of servicing that this design supports is relocation; i.e ConeXpress is designed to extend the operational lives of satellites through supplementing station-keeping ability, but it could also be used for orbit relocation. Therefore, the choice of a servicer depends on which form of servicing the provider is aiming to support, i.e. the need of the customer that the provider intends to fulfill.

7.4.2. Servicing Infrastructure

A service provider's servicing infrastructure consists not only of the servicer, but the supporting infrastructure for the servicer as well. The following are a few of the suggested elements to consider when developing a servicing infrastructure:

- Number of Servicers
- Number of In-Orbit Depots, if any
- Response time of servicer
- Automated vs. Telerobotic servicer
  - Ground station coverage/communications requirements
- Location of parking orbits
- Re-supply Options
  - Choice of Launch Vehicle
    (low risk launchers for high value payloads
    vs. high risk launchers for low value payloads)
  - Launch Site location
  - Rendezvous location
  - Re-supply to depot or servicer
- Business strategies
  - Network externalities
  - Required Return on investment
  - Co-operations/Coalitions/Monopolies/etc

Based on the service provider's choices concerning the elements in the servicing infrastructure, the service provider will have a minimum servicing price that corresponds to the design. The purpose of this thesis is not to look at the design of servicers, it is to examine the value that servicing can offer. Therefore, the design of servicer and the calculation of the minimum servicing price are left as future work.

7.5. **Conclusion**

It should be clear by now that the service provider is separate from the customer. The provider has his own decisions to make—design choices, costs structure, etc. What matters to the service provider is the development of a servicer that meets the customer's need. To begin the design of a servicer, the provider must understand the relationship between the forms of servicing and the customer's fundamental functions of servicing.

On the customer side of the market there are four fundamental functions that a customer seeks to fulfill the need for additional value: asset assessment, asset re-organization, asset restoration, and asset augmentation. The service provider has the ability to meet any one of these needs in a number of ways. The service provider has at his disposal six forms of servicing: inspection, relocation, refueling, recovery, repair, and upgrade. Because the customer is not concerned with the form of servicing, a service provider can use any one of the forms of servicing to meet customer need. The goal of the service provider is to design a servicer that has a low enough servicing price such that the servicer meets customer need, thus creating a feasible OOS market.

The next chapter will discuss the next step in the evaluation of OOS, determining a feasible OOS market. Chapter 8 compares the customer's maximum servicing price with the provider's minimum servicing price for a given form of servicing. A feasible OOS market will exist when the two sides of the market have a common range of servicing prices. To determine if such a range exists, all that needs to be done is to overlay the customer's maximum servicing price with the provider's minimum servicing price and determine if there is an overlap between the two curves.

Chapter 8. The Final Step: Determining the Feasible OOS market

The final step in the evaluation method is to determine if a feasible OOS market exists. For a feasible market to exist, the price a customer is willing to pay for servicing must be greater than the provider's minimum price. The feasible OOS market is found by overlaying the customer's maximum servicing price and the provider's minimum servicing price. This chapter will walk through the steps of this process and later describe an example of determining the feasible OOS market for the servicing case found in Chapter 4.

In addition to determining the feasible OOS market, the overlaying of the two cost curves is representative of the classic supply and demand curves. This chapter discusses how the customer's maximum servicing price represents an "implied" demand curve with respect to servicing and alternatively how the provider's minimum servicing price represents an "implied" supply curve. Through the ability to describe the OOS market in the terms of supply and demand curves, an examination of how classic microeconomic principles can be used to effect change in the servicing prices is discussed. Through this discussion, certain ideas are presented on how one can affect the range of the servicing prices, thus changing the feasible OOS market.

This chapter concludes with a discussion of some of the remaining problems that OOS faces before OOS can become a reality. For example, certain legal issues that are brought about by the creation of a satellite servicing market are unclear and require attention. How certain policy choices by the United States may cause corporations to move off-shore. Conversely, how certain U.S. policies may prevent foreign service providers from servicing U.S. satellites. The legal and policy choices that are made with regard to these issues have the potential to have greater effects on the development of a feasible OOS market than either the economic or technical issues. Thus, the tangled web of legal, political, technical, and economic issues creates major trade-offs for the development of OOS capabilities. Both a service provider and national governments must understand the implications of these issues before the development of a feasible OOS capability can be developed.

8.1. How to Find the Feasible Servicing Region

The OOS market is a range of feasible servicing prices under which an interaction between the buyer and seller exists. Because it was assumed that the decisions of the buyer and seller are independent, the servicing prices for each side of the market can be found without regard to the other side of the market. The determination of these servicing prices was the focus of the previous chapters. To determine if a feasible market is present, the minimum servicing price found by examining the provider's side of the market is overlaid onto the maximum servicing price from the customer's side of the market. A feasible range of servicing prices for the service provider exists for all servicing prices greater than the minimum servicing price, while feasible servicing prices for the satellite operator exist for all servicing prices below the maximum servicing price. If any overlap exists between the two servicing prices, then a feasible market for OOS exists within the overlapped region. For instance, if the customer's maximum servicing price is greater than the provider's minimum servicing price, a feasible OOS market exists for all servicing prices between the minimum servicing price and the maximum servicing price. However, if the minimum servicing price is greater than the maximum servicing price, no overlapping range of servicing prices exists and as a result no market exists.

An added benefit of the independence between the buyer and seller is that it allows for the comparison of multiple service providers to fulfill the need of a single customer. This can be looked at in two ways. The multiple sellers can represent a service provider that has multiple forms of servicing. Each form of servicing can meet customer need, but in a different way. i.e. in the case of life extension, both refueling and relocation fulfill a customer's need for asset restoration. Because each form of servicing has a unique minimum servicing price, each form of servicing creates its own unique servicing market. Thus a service provider can choose between servicer designs and determine which design creates the largest feasible servicing region. The largest feasible servicing region is the overlap region that consists of the largest range of servicing prices and thus has the greatest chance of delivering value to both side of the market through bargaining.

Alternatively, the ability to overlay multiple servicing prices can be looked at as multiple service providers, each with its own servicer design that is competing for the business of the customer. Here a customer can determine which service provider offers the lowest servicing price while still creating value. Whichever way the situation is examined, the ability to compare multiple sellers with a single buyer clearly represents the traditional idea of a competitive market: different forms of servicing are demand substitutable.

8.1.1. Customer Supply

On one side of the market is the customer. In general, as the servicing price a customer is charged increases the value that is delivered to the customer decreases, see Figure 8–1. When the value from servicing begins to decrease the customer demands less and as a result the range of feasible servicing prices decreases. Thus, as servicing price increases customers demand servicing less. The servicing price above which the customer would no longer demand servicing is the maximum servicing price. This same conclusion was reached in Chapter 4 where it was shown that as the servicing price increased the customer was delivered less and less value and therefore demanded servicing less. Recall, Figure 4–2 portrays the customer's servicing price as a function of the value of the option. In that figure, the point at which the value of the option was zero represents the maximum servicing price. Another example, Figure 5–1, shows the customer's maximum servicing price as a function of time. Thus, the customer's maximum service price represents a kind of traditional customer demand for servicing.

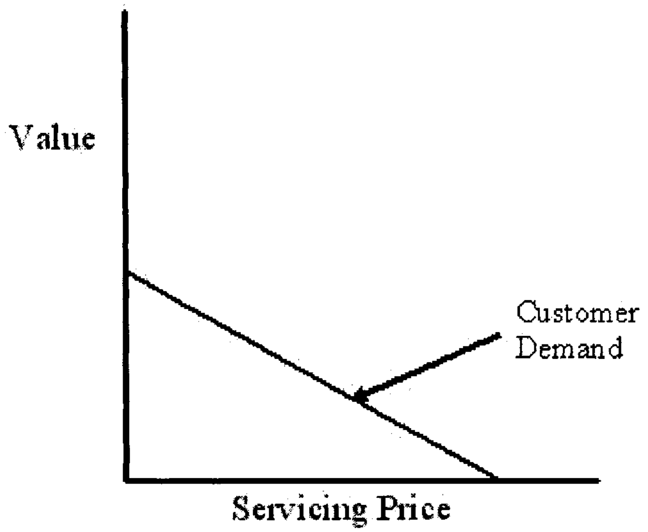


Figure 8–1: Implied Customer Demand

8.1.2. Provider Demand

On the other side of the market is the provider. Like the customer's implied demand function, the provider's minimum servicing price represents the provider's implied supply. It is expected that, as the service price increases, the provider can provide a better service to the customer, which results in higher customer value (Figure 8–2). No explicit minimum servicing price was found in this thesis; this work is being left for future research. It is assumed that the minimum servicing price is fixed in time and is a function of the value it delivers to the customer. However, in reality, the minimum servicing price would probably change as a function of time based on the economics behind the service provider's servicing architecture.

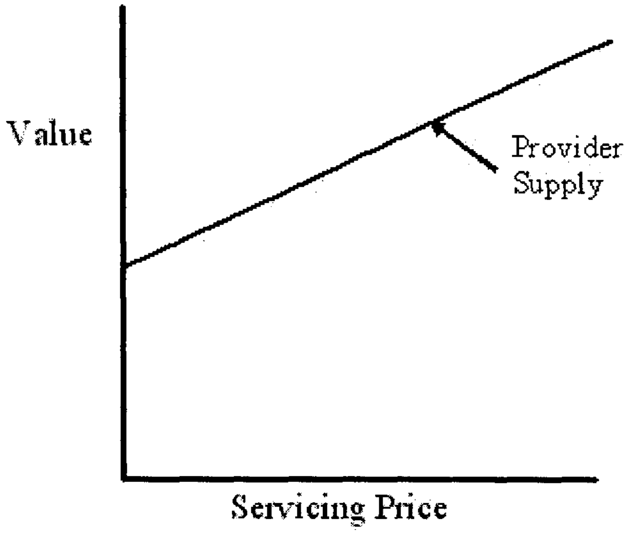


Figure 8–2: Implied Provider Supply

8.1.3. Creating an Overlap

The entire purpose of the evaluation method has been to resolve the uncertainty about the potential OOS market. After understanding the value of OOS and determining the customer's maximum service price, a provider is able to determine the appropriate form of servicing to meet the customer's need. After the provider has determined the customer's maximum service price, the provider can overlay multiple servicing architectures and determine if these architectures meet the customer's need. This process allows providers to test the feasibility of their designs without the need to continually recompute the customer's maximum servicing price. If any overlap exists, as in Figure 8–3, a feasible OOS market exists for the servicing prices within the overlap. If no overlap exists, as in Figure 8–4, no feasible OOS market exists because the customer and provider do not share a common servicing price.

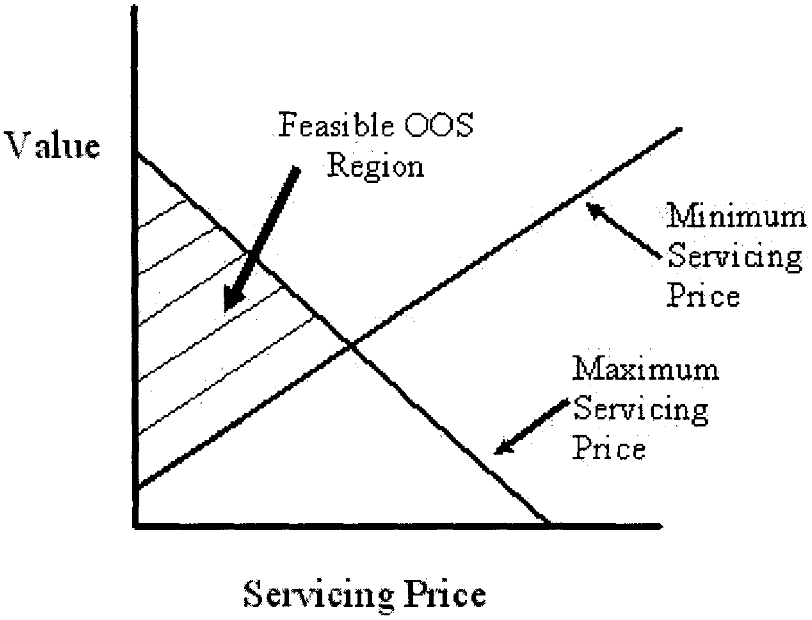


Figure 8–3: Conceptual Example of a Feasible Service Market

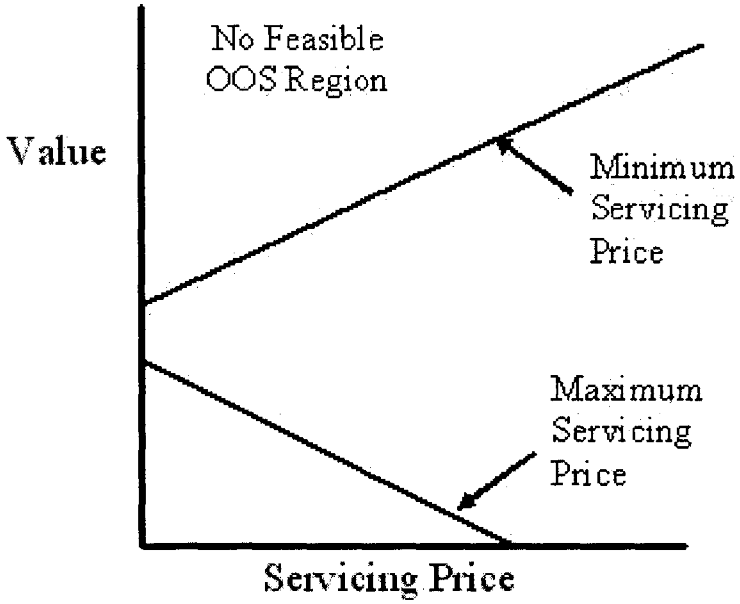


Figure 8–4: Conceptual Example Which Lacks a Feasible Service Market

8.1.4. Actual Servicing Price

Recall from Chapter 2 that the purpose of separating the market was to examine the interaction between buyer and seller in order to determine the actual price of servicing. Up until now only the minimum servicing price and the maximum servicing price have been discussed. The sought after actual servicing price exists somewhere between these two servicing prices. Figure 8–5 gives a representation of the theoretical actual price of servicing. Although the actual price of servicing in not computed in this thesis, this point – the intersection of the actual customer demand curve (D,Act) and the actual service provider supply curve (S,Act)- must exist somewhere to the left of the intersection between the customer's maximum demand (D,Max) and the provider's minimum supply (S,Min). Thus, the actual servicing price can only exist at a point within the overlap region. However, if the overlap region defined by the maximum and minimum servicing prices is not large enough, no actual servicing price may exist for a given value level because the service provider supply curve may be greater than the actual customer demand curve. To create the greatest chance that an actual servicing price exists for which satellite servicing makes commercial sense, a service provider wants to make the feasible range of servicing prices between maximum demand and minimum supply as great as possible.

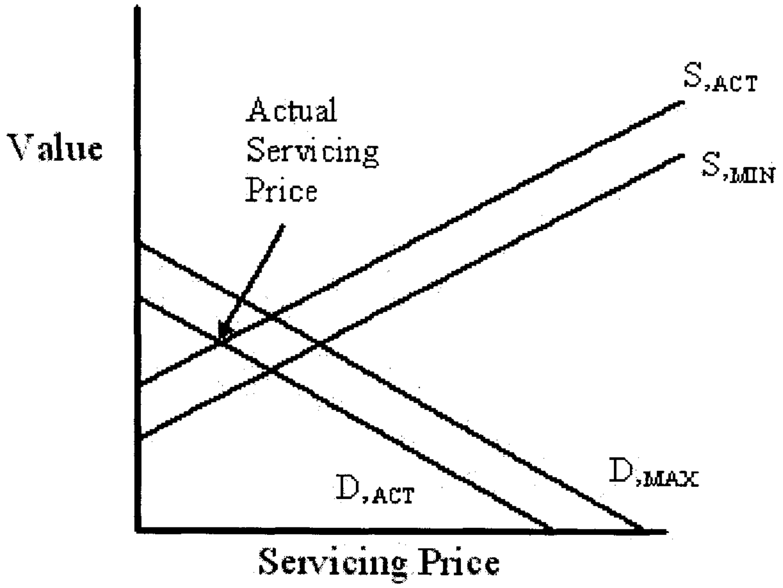


Figure 8–5: Theoretical Actual Servicing Price

8.1.5. Comparison of Multiple Servicer Designs

Figure 8–6 depicts how different forms of servicing (represented by different S,Min lines: {S1, S2, S3}) can create different feasible OOS cases. Here a service provider is able to evaluate multiple architectures and determine their feasibility by looking for the intersection of supply and demand curves. By changing the design of the servicer, the service provider is able to create a supply curve that results in a greater range between the maximum demand and minimum supply curves, thus creating a greater chance that a feasible servicing market exists.

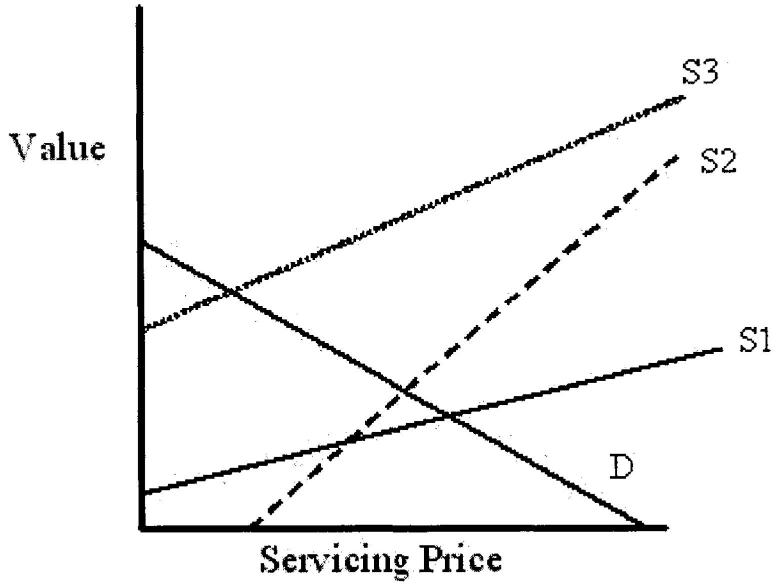


Figure 8–6: Overlaying of Multiple Servicer Designs

8.1.6. Example

At this point, the customer's maximum servicing price and one, if not more, provider minimum servicing prices have been determined. The feasible servicing region is determined from the viewpoint of the satellite operator. Figure 8–7 and Figure 8–8 show the results from the Intelsat 801 case in Chapter 4. It was assumed that in this case the satellite operator, at a minimum, would like an expected 10% return on investment. Thus, the satellite operator will only choose to service if the servicing price is at or below the servicing price where the expected value that results from a single servicing mission is at least 10% of the cost of that servicing mission. This point was referred to as the "true" maximum servicing price in Chapter 4- See:.4.3.3: The "True" Maximum Servicing Price

While a larger servicing price still creates value, the 10% threshold cut-off was assumed so that the price of servicing was not too disproportional to the value of the option. The creation of the "true" maximum servicing price is therefore an attempt to capture some of the customer's post-process decision analysis that would be used at the time of servicing. Note: this is not the same as the customer's utility function; the threshold cut-off is simply a post-process analysis attempting to describe the likely decision of a satellite operator.

8.1.6.1. Single Year Life Extension Case

The first case to be examined is the case of life extension where only a single year of additional life is provided per servicing mission. Figure 8–7 shows the different threshold cut-off values for the customer's return as a function of the number of servicing missions. For example, if the satellite operator plans to only service the satellite once, the maximum servicing price, based on the 10% expected return on investment requirement, for a single servicing mission is a little less than $40M. This point is represented by the intersection of the 2012 value line (solid) with the one mission servicing cut-off (dashed). All servicing prices to the right of this price on the 2012 line represent feasible servicing cases where servicing can provide value, but based on the mission cut-off price the operator will not choose to service.

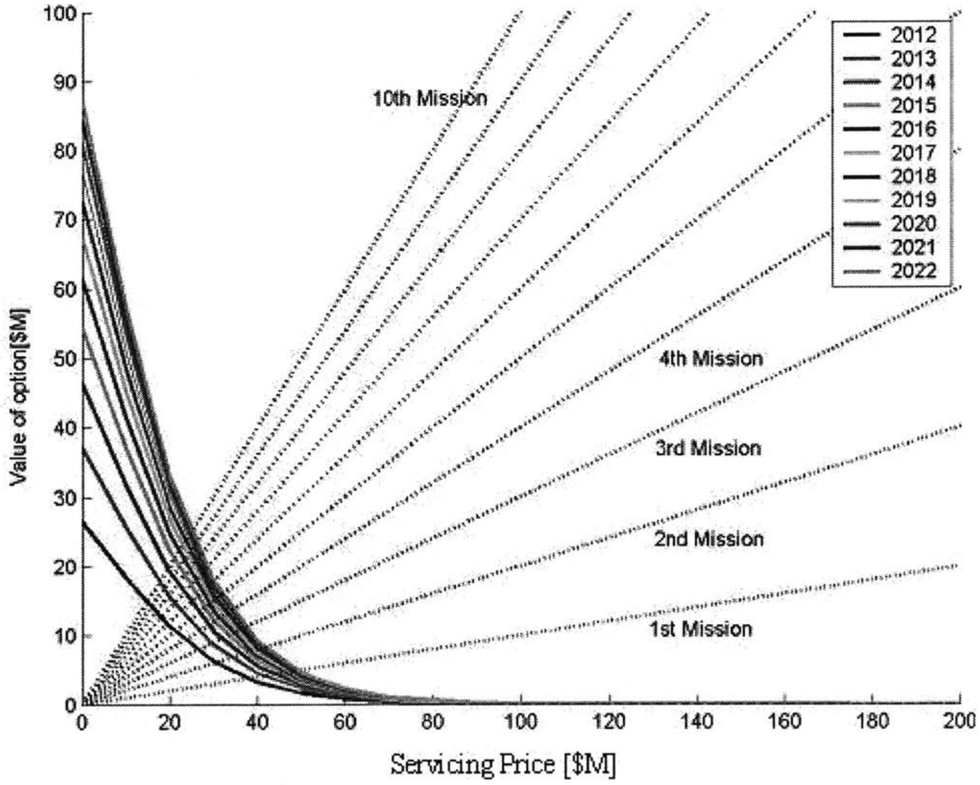


Figure 8–7:

Intelsat 801 Life Extension Case, Single Year Life Extension, 10% ROI Cut-Off

In Chapter 4 it was shown that the expected value from servicing increased as additional operational years were provided. However, based on applying the 10% threshold value, the satellite operator's maximum servicing prices actually decreases as additional operational years are delivered. For example, the maximum servicing price for two missions is around $100M, but the "true" maximum servicing price reduces to about $37M per service. Similarly the maximum servicing price for 10 missions was also about $100M, but the threshold cut-off reduces the "true" maximum servicing price to about $25M per service.

In effect the threshold cut-off shows that as additional years of operational life are provided, less value is delivered to the customer. Therefore, as the servicing price increases the customer will demand fewer additional servicing missions. Thus, by finding the "true" maximum servicing price, one can determine the classic demand curve that describes the customer's relationship between units supplied, in this case the number of servicing missions and the price of those units. To find the actual demand curve, the number of servicing missions that are available to the customer—in this case the number of additional operational years— is used to determine the customer's "true" maximum servicing price for each mission. The customer's demand curve is determined by plotting the "true" maximum servicing price as a function of the number of servicing missions.

8.1.6.2. Multi-Year Life Extension Case

What effect does lengthening the number of additional years provided by the servicing mission have on the customer's demand curve? Figure 8–8 provides four threshold values for the case where the service provider provides three years of additional operational life with each service instead of just one. In this case it was assumed that a service provider would purchase life extension and wait the full course of the extension before purchasing the option again. In Figure 8–8 the first servicing mission would provide operational life until 2014, the second mission until 2017, and the third until 2021. Here, the operator's "true" maximum servicing price for a single mission is increased to about $70M (intersection of the 2014 line and the first threshold cut-off). Similarly, the "true" maximum servicing price for two life extension missions is increased to about $67M, and three missions is increased to about $62M. Once again, the customer's maximum servicing price decreases for each consecutive servicing mission. However, the extension of the length of the additional operational life provided by the servicing missions shifts up the value of the life extensions, which has the effect of shifting the 'true' maximum servicing price to the right.

The customer's actual demand curve is found in the same way as described in the single year case above. The application of the threshold cut-off supplies an additional constraint on the feasible servicing prices, but allows for a service provider to compute the actual customer demand curve, as opposed to the implied demand curve discussed earlier.

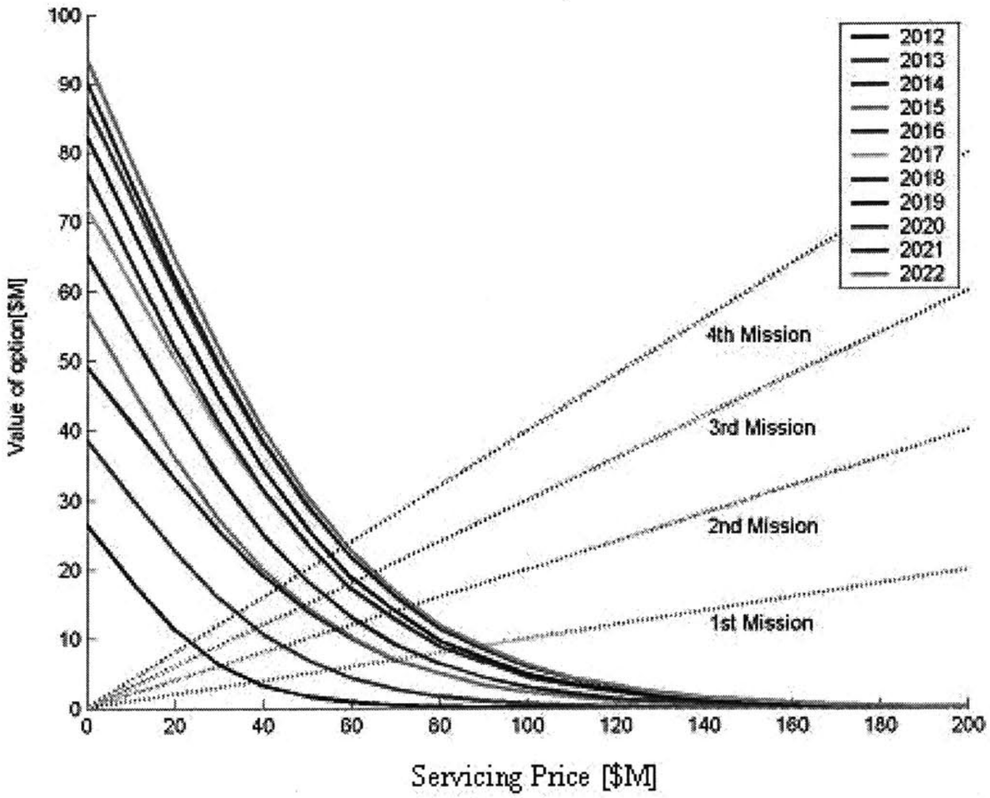


Figure 8–8: Intelsat 801 Life Extension Case, Three Year Life Extension, 10% ROI Cut-Off

8.1.6.3. Adding the Supplier Perspective

After the new range of feasible servicing prices is determined by adding the constraint of the operator's threshold cut-off, the next step is to switch to the provider perspective. The provider has several minimum servicing prices based on the different forms of servicing. For instance, servicing architecture A might have a minimum servicing price of $30M per service, while architecture B has a minimum servicing price of $60M. Both architectures have the same end result of providing the customer with the same value, in this case a single additional operational year, but both architectures fulfill that need in different ways. Architecture A could represent a refueling type servicer while architecture B could represent a space tug type servicer.

The service provider can determine which architecture creates the greatest range of servicing prices by overlaying the minimum servicing price for the architectures on the plot of the customer's maximum servicing price. If a service provider were to design architecture A, represented by line A, the service provider would expect that on average the satellite operator would only purchase the option to extend three or four times. The number of desired servicing missions being represented by the point at which the minimum servicing price is at or just below the "true" maximum servicing price for that number of servicing missions. For example, if the operator desired to only service their satellite once, the "true" maximum service price would be \$40M. The feasible range of servicing prices would be defined as the servicing prices between the provider's minimum price of \$30M and the customer's "true" maximum price of \$40M. Thus, the feasible market would exist for this servicing mission because the minimum servicing price was below the "true" maximum servicing price.

In the event that the provider designed architecture B, represented by line B, no feasible range of servicing prices would exist. This is because the minimum servicing price for architecture B is greater than the operator's "true" maximum servicing price, \$60M>\$40M. Therefore architecture B would not meet the customer's demand and thus would not create a feasible OOS market.

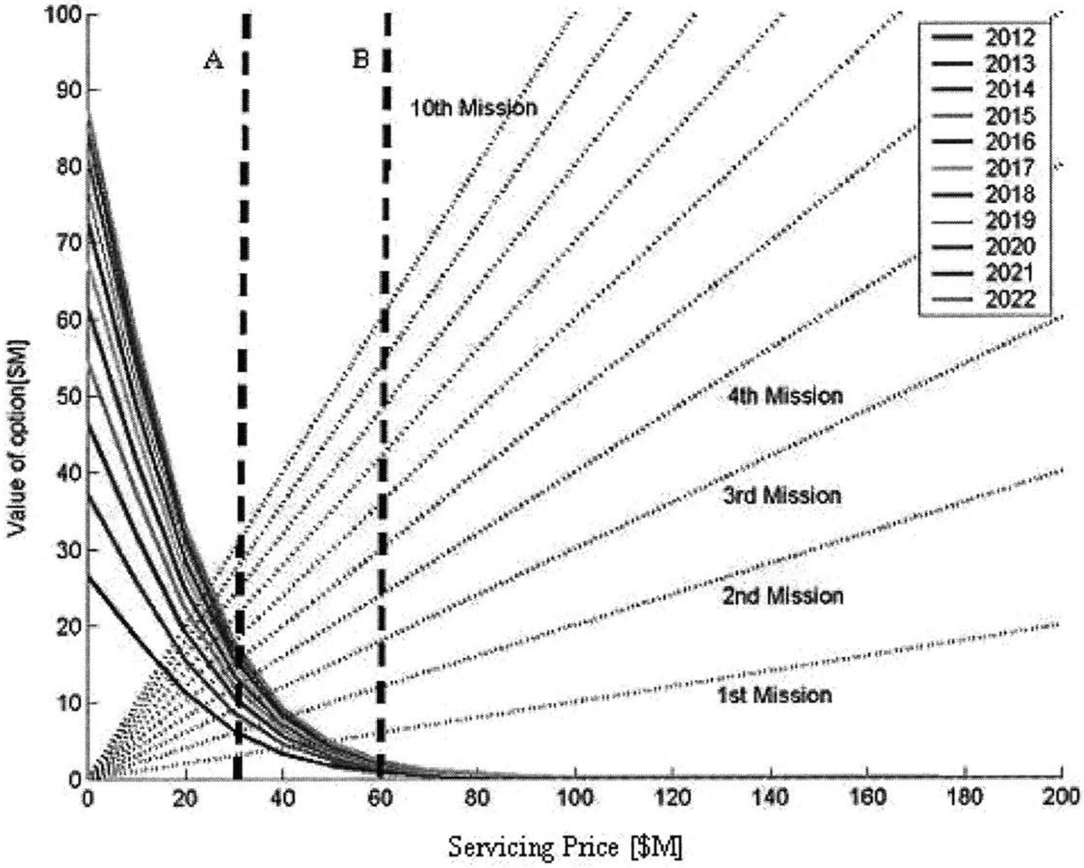


Figure 8–9: Overlaying Minimum Servicing Price with Maximum Servicing Price, Intelsat 801 Case

8.2. Future Applications

By essentially describing OOS markets as a function of service provider supply curves and satellite operator demand curves, classic microeconomic principles can be applied to maximize the feasible range of servicing prices. The most direct effect that can be examined here is that of policy intervention, more precisely the effect of a tax or subsidy on OOS. A subsidy would be seen as a uniform positive shift up in the customer's demand curve (maximum service price), or a uniform shift down in the provider's supply curve (minimum servicing price). Similar to traditional supply and demand curves, subsidies increase the feasible range of servicing prices and thereby increase the number of feasible designs. By increasing the number of designs that meet customer need, greater competition can be created through competing designs. As competition increases servicing price will decrease, thus making OOS more attractive.

Thus, a potential policy decision for a government could be the creation of a government subsidy or grant for OOS architectures in order to foster innovation and competition.

The other microeconomic principle that can directly affect the range of servicing prices is a tax. A government might want to levy a tax on OOS for two reasons: to gain additional revenues to support launch infrastructures or to collect corporate tax from profits generated by the service provider. Either reason for levying a tax would result in a decrease in the feasible servicing region by either lowering the customer's maximum service price or increasing in the provider's minimum servicing price. The end effect of imposing a tax on OOS would be a reduction in the feasible region of servicing that would make it harder for multiple service providers to compete; thereby making satellite servicing less attractive.

8.3. Remaining Unanswered Questions

Although it is clear that a subsidy would benefit the development of OOS, the question remains why would a government offer a subsidy? Possible reasons include: promotion of space commerce, promotion of technology development, promotion of new satellite design, and increase in a military advantage over its adversaries. However, in the past these arguments alone have not convinced the United States government as they have the European Union. Given the current state of U.S government funding, government subsidies for the development of OOS are more likely to occur outside the U.S. rather than within. But if one wanted to obtain U.S government funding for OOS, what would be the best approach?

8.3.1. Promotion of OOS Development by the United States Government

Why would the U.S government promote/support the development of OOS? What part of the U.S government is likely to benefit most from OOS? In examining the players within the U.S. government, the best approach would probably be to focus on military applications.

In looking at past U.S. government actions, the U.S. military has supported new technology developed when that technology would give the U.S military a decisive advantage over its adversaries. At the same time, it is well known that military technology will probably spill over to the commercial sector, thus allowing for the commercial development of the technology. The question that must be answered is whether or not OOS should be any different. If the U.S. military were to adopt and support the development of OOS, OOS must provide the U.S. military with an advantage over its adversaries.

Chapters 5 and 6 show that one of the characteristics of a feasible servicing market is the case of integrating technologies that result in significant increases in value. Based on this finding, the U.S. military is likely to benefit from the capabilities of OOS. The U.S. military could benefit from OOS because OOS could allow the military to integrate new technologies into their observation satellites. Recall that Joppin showed that OOS made sense in the case of the Hubble Space Telescope because the optical systems allowed for magnitude increases in value. These magnitude increases could probably be replicated in optical satellites used by the military. Thus, OOS could provide the military with the ability to generate significant improvements in their observation satellites and thereby significantly increase the military's advantage over its adversaries.

When an OOS infrastructure is up and running, OOS could deliver additional strategic advantages to the U.S. military such as: satellite responsiveness, orbit relocations, etc. The U.S. military, as opposed to the commercial satellite industry, is thus the likely player in the space industry that would benefit the most from OOS. When the U.S. military has bought into the idea of OOS, the technologies developed through U.S military support would eventually spill over into the commercial realm thus allowing for the creation of a commercial OOS market. Therefore, if one seeks to attain government subsidies for OOS from the United States government, one should focus on military based customers.

8.3.2. Unanswered Legal Questions

Aside from the economic and technical problems that OOS faces, there are additional inherent legal questions that must be answered before a competitive satellite servicing market can be developed. The following section explores three areas of legal uncertainties that can have an effect on the development of future OOS infrastructures. The legal question pertaining to the development of OOS are: determining the assignment of liability for damages that can result from servicing, corporate tax policy pertaining to revenues generated from providing OOS services, and export control concerns that might arise during the OOS process.

8.3.2.1. Liability for Damages

Generally two bodies of space law oversee the operation of satellite in space; international law and national law. Since 1959, international space law has been overseen by the United Nations Committee on Peaceful Uses of Outer Space (COUPOS). Since its creation COUPOS has created five international legal instruments and five sets of legal principles governing space-related activities (COUPOS, 2004). The relevant COUPOS treaties that pertain to OOS are the 1967 treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, the 1972 Convention on International Liability for Damage Caused by Space Objects, and the 1975 Convention on Registration of Objects Launched into Outer Space (Richards et. al, 2005). In terms of national law, the relevant national legal principles with regard to space operations tend to criminal law pertaining to the restrictions on commercial satellite operations.

The problem that current international space law creates for OOS is primarily based around liability and legal rights to property. In this thesis, it was assumed that a non-governmental agency would be in control of OOS activities, namely that the service provider would be a commercial company. What does the COUPOS treaties have to say about commercial activities in space? According to Article VIII of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, a state "shall retain jurisdiction and control over such object (satellite, service, etc), and over any personnel thereof, while in outer space or on a celestial body." Article VI also states that a State "shall bear international responsibility for national activities in outer space... whether such activities are carried on by governmental agencies or by non-governmental entities." What this means is that the State from which a satellite, or servicer, was launched is responsible for the activities of that satellite. Thus, when a servicing satellite causes damage to a target satellite, who is responsible for the damages?

The concern over damages is answered in the 1972 Convention on International Liability for Damage Caused by Space Objects. Article II of the liability convention provides that a launching State is absolutely liable for damage caused by its space objects in space, and Article III provides that this liability is determined by fault (Richards et. al, 2005). Therefore under the current legal standings, if a commercial satellite servicer were to attempt to service a satellite in space and that satellite was launched from a different State, then the State (not the commercial company) from which the servicer was launched would be liable for the damages resulting from servicing. However, if the servicer and satellite were launched from the same State, international space law would not apply and the national laws of the state would come into play.

The problem of liability is only compounded in the event of third party effects. Recall from Chapter 3 that one form of risk that exists is that of third party effects. Third party effects are the case where servicing fails and due to that failure orbital debris may be released that affects a third party's satellite. In the case where all three satellites are launched from the same State, the national laws of that State would take effect as before. However, how would liability disputes be handled if the three satellites were not launched from the same State?

Assume that a servicer was launched from the United States and was servicing a satellite launched from the United States. In the course of servicing, the servicer caused damage to the satellite which resulted in the creation of orbital debris. Under the current international law, the dispute over damage caused by the target satellite would be settled by U.S. law. However, assume that the debris that was released by the failure caused damage to another satellite that was not launched from the United States, a North Korean military satellite for example. Although the initial dispute was resolved within the Unites States court system, the third party damage created would have to be settled by international law. According to international law, the United States would be liable for the damages to the North Korean military satellite despite the fact that the servicer was launched by a commercial entity. Imagine the legal nightmare, let alone the political crisis, that could result.

Additionally, two other complications can arise with third party effects:

1) What would happen if the servicer was launched from state A, the target satellite from state B and the third party satellite from State C. According to Article VI of the Convention on International Liability for Damage Caused by Space Objects "the burden of compensation for the damage shall be apportioned between the first two States in accordance with the extent to which they were at fault; if the extent of the fault of each of these States cannot be established, the burden of compensation shall be apportioned equally between them." One can expect that this situation would result in arguments over who was responsible for the initial damage (State A or B), and then who would be responsible to pay for the third party damages to State C.

2) How would liability be placed if a commercial servicer were launched in international waters? According to Article I of the Convention on International Liability for Damage Caused by Space Objects, "launching State" means: "(i) A state which launches or procures the launching of a space object; (ii) A state from whose territory or facility a space object is launched." It would appear then that, if a satellite was not procured by a given State and was not launched from a particular State's launch facility (for instance in international waters), that satellite would not have a "launching state" according to Article I. How then would liability be placed on an international scene if a servicer launched from international water was to cause damage to any satellite? Could the commercial company be held liable under this condition? The current legal framework is unclear. Table 8-1 provides a quick reference to current legal instruments governing potential satellite servicing operations. Thus, some of the legal inadequacies, in particular those involving

liability for damages, will have to be worked out before a commercial satellite servicing market is established.

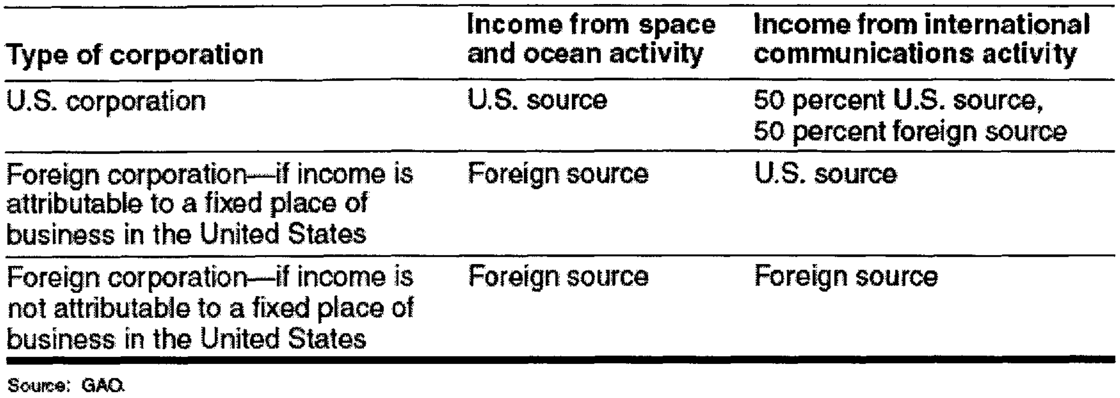
Table 8-1: Relevant international and national legal instruments (Richards et al, 2005)

1967 Outer Space Treaty	Article VIII: Provides a state jurisdiction and control over its registered space objects
1972 Liability Convention	Article II: Holds a state liable for damage caused by its launched space objects
	Article III: Determines liability by fault
	Article IV: Holds states jointly liable if a collision of their space objects causes third party damage
1973 Telecommunication Convention	Bans harmful interference to the communications of other states
1975 Registration Convention	Requires states to maintain a registry of objects launched into space
US Criminal Law Title 18, Section 1367	Makes interference with satellite communications a federal offense

8.3.2.2. Corporate Tax Policy

The first suggested reason for levying a tax on satellite servicing, for the support of launch infrastructure, seems unlikely. However, taxing commercial revenues without a doubt occurs today and would not require a second thought on the part of government agencies. This raises an interesting question for both U.S federal and state governments; can federal and state governments tax corporate business that is conducted in space? Another interesting question, if the federal and state governments are able to tax business conducted in space, would this form of taxation drive U.S.-based corporations off-shore? Surprisingly enough this question has come up before and the answer is clear in one case and vague in another.

Table 8-2: Basic Statutory Rules for Determining Whether Income Is U.S. or Foreign Source (GAO, 2004)



Type of corporation	Income from space and ocean activity	Income from international communications activity
U.S. corporation	U.S. source	50 percent U.S. source, 50 percent foreign source
Foreign corporation—if income is attributable to a fixed place of business in the United States	Foreign source	U.S. source
Foreign corporation—if income is not attributable to a fixed place of business in the United States	Foreign source	Foreign source

Source: GAO.

8.3.2.2.1. Federal Taxes

According to a GAO report, the rules that determine federal tax on a corporation's income from business conducted in space or the ocean depend on where the corporation is incorporated and the source of the income. The GAO report describes two forms of corporations, foreign and domestic, and two forms of income sources, space/ocean activity and international communications. Table 8-2 summarizes the basic statutory rules provided by the GAO report. Under the basic statutory rules, a U.S incorporated corporation whose income is derived from space or ocean activity, no matter the activity, is classified as a U.S. source and therefore subject to U.S federal taxes. However if the U.S corporation engages in international communications, i.e. provides communication capabilities to a foreign country, the corporation's income is treated as "50 percent from U.S. sources and 50 percent from foreign sources (GAO, 2004)" and is thus taxed accordingly. But, claims to U.S. taxes cease in cases when a corporation is foreign-based, not U.S.-based.

In cases of non-U.S. corporations, a foreign corporation's income from space activity is viewed as foreign source and thus subject to only foreign taxes even if that corporation does business within the United States - with one exception. In addition, even if a foreign corporation has a fixed place of business in the United States, the corporation is not responsible for paying federal taxes. The one exception to the exclusion from avoiding federal taxes is the case where "a foreign corporation has an office or fixed place of business in the United States [and] all of its international communications activity income [is] attributable to such an office or business. "Under these circumstances the corporation's income is treated as U.S.-source (GAO, 2004) and is therefore subject to federal taxes. Thus there is some prevention, in cases of international communications, by the United States government against allowing U.S. based companies from move off-shore in order to avoid federal taxes.

For the most part the United States' federal tax policy with regard to space commerce is sound; U.S corporations that generate revenues through space communications activities involving U.S-based ground sites are subject to federal taxes, or 50% of a the revenues are subject to federal taxes in cases where revenues are generated through international communications. As for non-U.S. corporations, foreign corporations pay foreign corporate taxes for space activity to the foreign country from which it originated unless that corporation provides communications services to the United States, in which case the source of the communications revenue would be viewed as U.S. source and thus taxable. However, OOS is not a form of satellite communications and thus the United States cannot capture taxes on revenues generated by foreign corporations even if that corporation has a fixed place of business in the United States. Thus, a loophole might exist in the collection of federal taxes in the case of on-orbit servicing. In response to this loop-hole, U.S based service providers may move-off shore in order to avoid paying federal taxes.

8.3.2.2.2. Local/State Taxes

The implications of local or state corporate tax policy on OOS are murky at best. The reasons for the debate surrounding taxing a corporation's income from space activities on the local level rest on problems with assigning jurisdiction. Take for example the problems that have arisen with taxing e-commerce. The main issues regarding taxing e-commerce are a concern of jurisdictional assignment-- i.e. which governmental entity shall have the authority to tax a transaction that spans several jurisdictions (GIPI, 2005)? In general, the collection of taxes on commerce at the state level is accomplished through sales taxes. Sales taxes are paid by the consumer, but they are collected by the merchant. But the problem with taxing e-commerce led to a U.S. Supreme Court decision. In 1992, the US Supreme Court held that a state cannot require a business without any physical presence inside its borders to collect taxes on sales to residents within its borders (Quill 1992). Thus, a local government cannot collect sales taxes in cases where business was conducted with a company whose physical presence is outside the state's borders. Thus, due to the fact that e-commerce companies exist in cyber-space, many argue that e-commerce cannot be taxed at the local level because an e-commerce company does not have a physical presence in a state.

To temporarily resolve the dispute, in 1998 the US Congress imposed a three year "moratorium" on "discriminatory" or "multiple" taxes on Internet commerce, by using its power to preempt state laws on matters affecting interstate commerce. However, the moratorium only allows e-commerce to avoid taxes in cases where the type of business involves internet transactions; however, internet sales can be taxed according to state law. The moratorium was extended in 2001 for a two year period and became known as the Internet Tax Freedom Act (ITFA). As of August 2003, the US Congress was considering making the moratorium a permanent ban (GIPI, 2005).

Despite the future actions of congress, the main problem that arises with taxing e-commerce is defining a company's location and thus assigning jurisdiction. "Existing tax systems tend to determine tax consequences based on where the taxpayer is physically located. The e-commerce model enables businesses to operate with very few physical locations...also, some business assets, such as servers, are not necessarily tied to a single physical location, but can easily be relocated without any interruption to business operations. That is, the location of the server is not relevant for business purposes and thus, may not be a logical taxing point (Nellen, 2001)." The problem over jurisdictional definition exists in the same way for satellites. One could argue that, based on the current debate and legislative history around e-commerce, a purely space-based enterprise does not have a physical presence that falls under the jurisdiction of a local government. Even though a ground station would be physically located within the jurisdiction of a local government, one could argue that a ground station, like a server for the internet, can easily be relocated without any interruption to business operations. Thus, ground stations are not a logical taxing point for local taxes. Therefore, for the time being, local or state governments appear to not have the jurisdiction over taxing sales on space-based business.

While the debates about preventing taxation of e-commerce support the prevention of state taxation for on-orbit satellite servicing, the same debates actually lend support for taxing satellite servicing on the national level. The problem with taxing e-commerce at the state level was assigning jurisdiction, or who owns what on the internet. However, based on the COPOS treaties, a nation retains jurisdiction over a satellite that was launched from within that nation for as long as that satellite is in space. Due to the fact that the U.S is responsible for any satellite launched from within the United States, the U.S. should be well within its rights to require that taxes be paid on the business conducted by that satellite no matter where the corporation was incorporated. Since the business does not take place within a given state in the United States, a corporation cannot be held liable to pay state taxes. On the same note because a nation has responsibility over any satellite launched from within that nation, it is well within that nation's right to tax the business of that satellite. Therefore, the current taxation definition of income source for the United States, described by the GAO report, could be extended to include space businesses where the satellite in question was launched from within the U.S., even if the owner of that satellite was not based within the United States.

8.3.3. Does Export Control Apply

A major concern that runs throughout the aerospace industry is export control. Export control applies to the export of controlled U.S technology to either foreign countries or foreign nationals within the United States. But does it apply to in-space applications? It certainly does! Although U.S. technology may not be transferred to a foreign country through space business, export control applies to space when information about controlled technologies is transferred to a foreign nations or its citizens no matter if they are in space or not.

In the case of OOS, export control would apply if a U.S based satellite was serviced by a foreign based servicer. While the U.S may not be concerned with the servicer transferring knowledge or information to the satellite being serviced, the U.S is certainly concerned with transferring knowledge or information about the satellite to the servicer. One may assume that any form of servicing will result in satellite servicer gaining some form of knowledge about the target satellite. Recall satellite inspection, assessing the physical state of the satellite, is the building block of all forms of servicing. It does not matter whether the knowledge of the target satellite is intentional or unintentional. Any form of satellite servicing will result in information transfer that concerns the target satellite to the satellite servicer. Due to the fact that almost all technology onboard a satellite is controlled under the U.S. Department of State's munitions list, any U.S. satellite operator that has a satellite serviced by a foreign servicer would potentially be in violation of U.S Export Control Law.

While the limits imposed by U.S. export control law may limit innovation by preventing foreign servicers from servicing U.S satellites, U.S export control also has the effect of protecting U.S. companies from commercial competition. Is this a fair trade-off? This of course is not something that can be answered in this thesis, but export control could be used as a lever by the U.S government to prevent U.S corporations from moving off-shore by restricting foreign servicers from servicing U.S-launched satellites.

Due to the potential of high revenues from satellite servicing and the fact that corporations that launch servicers from within the United States are likely to be required to pay federal taxes on their business, what is the likely reaction by the commercial satellite service provider? The likely reaction, as it was previously stated, is that satellite service providers are likely to move off-shore in order to avoid U.S federal taxes on their business. But, in moving off-shore, these corporation may restrict themselves from being able to service U.S launched satellite due to export control policies. The question that must be answered by the satellite provider is whether or not moving off-shore is a sound business practice or is it simply a tradeoff between the lesser of two evils?

The unanswered legal questions create quite a dilemma for prospective OOS companies and governments in which these satellite servicers could potentially be launched. Should a government be able to restrict the servicing of satellites that were launched within that state to only servicers that were launched from that state? If so this would benefit the government by allowing the government to avoid potential liability in cases of servicer failure and maintain export control, but this would also limit the potential for international business and innovation on the part of service providers. The decision that a government should make in such cases is unclear. Clearly, the current legal precedents are not sufficient for handling the creation of an OOS market. Therefore, on-orbit satellite servicing has additional obstacles that must be tackled before the technical and economic questions can be discussed.

8.3.4. Getting U.S. Satellite Manufacturers Onboard

A final roadblock in creating an OOS architecture is the need to get satellite manufacturers to accept the idea of OOS. The case has already been made that satellite operators would benefit from OOS capabilities if they existed. In fact these operators would be willing to pay higher satellite costs to gain additional value provided by OOS. However, what incentives do satellite manufacturers have for changing the paradigm of their satellite design? Will slight increases in the selling price of serviceable satellites outweigh the additional costs that manufactures would be required to spend on the development of these satellites? What needs to be determined is if satellite manufacturers, such as Boeing or Lockheed Martin would be interested in the development of more complex satellites or would these designs decrease their profit margins?

As it stands, the Aerospace industry revenues were on the order of $87 billion dollars in 2003. Over the past couple of years, the world aerospace industry as a whole appears to have been growing at a rate of 15% per year (McAlister, 2004). However industry growth has mainly been concentrated in one area of the industry. Figure 8–10 shows that since 1996 the percentage of the industry revenues associated with satellite manufacturers and launch providers has decreased from almost 35% in 1996 to about 20% in 2002. While satellite manufacturers and launch providers have seen a combined increase in revenues from $12.5B in 1996 to $15.8B in 2002, the satellite service sector of the industry has seen revenues increase from $15.8B in 1996 to $49.8B in 2002. Clearly the growth in the industry is concentrated on the satellite service provider and not the satellite manufacturers and launch provider. A statement by Jim Albaugh, president and CEO of Boeing Integrated Defense Systems, supports this conclusion. Jim Albaugh stated that "The commercial space market has eroded to a point where it is no longer a driving factor in either our satellite or launch services business." Clearly, the manufacturers of satellites and launch vehicles are not capturing the profit increases seen by the rest of the industry. If OOS will only add value to satellite service providers, what incentives do satellite manufactures and launch providers have to invest in new satellite design?

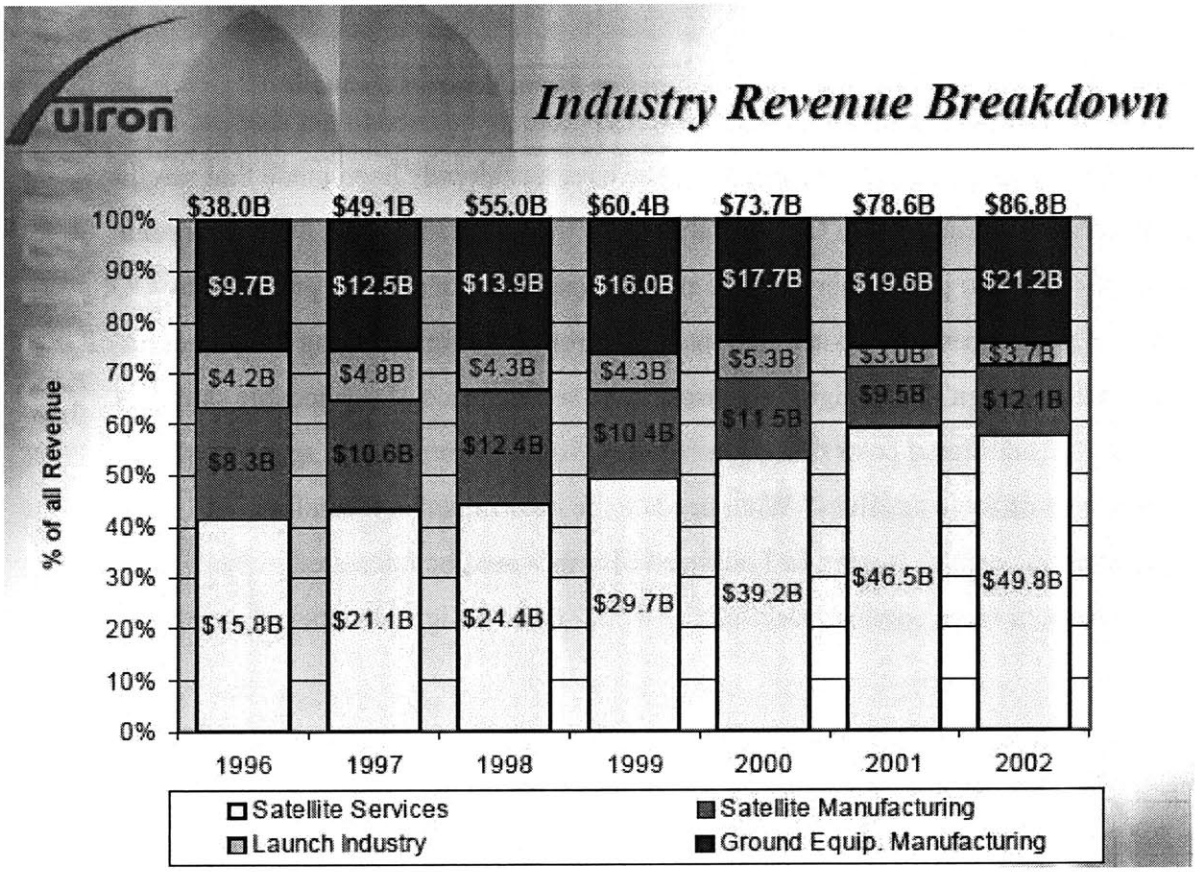


Figure 8–10: Breakdown of the satellite industry's revenues McAlister, 2004

The answer to the incentive problem may not rest in the space industry but in the automotive industry. Recall, the problem with current satellite design is the lack of accessibility. OOS however eliminates this problem by allowing satellites to be accessed via robotic servicers. In the automotive industry, a substantial portion of industry revenues is from the initial sales of cars, but another substantial part of the industry revenues come from aftermarket sales and service.

The aftermarket for cars exists solely because automobiles can be accessed. By eliminating the inaccessible nature of satellites, OOS has created the potential for an entirely new satellite aftermarket. A satellite aftermarket could consist of not only satellite manufacturers, who design serviceable satellites, but also satellite manufacturers and launch providers who develop and deliver replacement parts, new technologies, additional fuel, etc. Satellite manufacturers and launch providers can thus supply satellite service providers with needed replacement parts, not unlike how the automotive companies supply replacement parts to service shops. For example, satellite manufacturers would design new components or supply replacement parts that would then go to launch providers who would then place those parts in orbit on low cost launch vehicles. Once in space these parts would be delivered to the satellite service provider. It is out of the creation of a new satellite aftermarket that satellite manufacturers and launch providers can capture new undiscovered industry revenues. The potential of a satellite aftermarket, not the increases in price of a serviceable satellite design, should be what is needed to attract satellite manufacturers and launch provider to investing in OOS.

8.4. Conclusion

By examining the OOS market as two sides of a competitive market, a range of servicing prices is determined below which satellite servicing makes sense. As stated in Chapter 2, the first step in determining a feasible range of servicing prices is to determine the customer's maximum servicing price. Given the maximum servicing price, the customer's "true" maximum servicing prices can be determined based on customer interviews, or some other form of post process analysis. From the "true" maximum servicing price, a customer demand curve can be created for the number of servicing missions as a function of servicing price. Without calculating the customer demand curve, one is still left with the option of determining the customer's "implied" demand curve, defined by the customer's maximum servicing price.

The next step in the process is to determine the provider's minimum servicing price. This price is unique to not only the service provider, but the servicing architecture as well. With the minimum servicing price, a service provider can determine the feasible range of servicing prices in two ways: 1) The service provider can examine just the cases where servicing provides value to the customer. Thus, by overlaying the minimum servicing price with the customer's maximum servicing price, the service provider can determine if its service architecture creates a feasible range of servicing prices. 2) The other possible course of action for the service provider is to determine the actual price of servicing. To determine the actual servicing price, the service provider would need to determine any threshold requirements of the customer. From these threshold requirements, the provider can determine the customer's "true" maximum servicing price with respect to servicing. Then by overlaying the minimum servicing price with the "true" maximum servicing price, a service provider can determine the actual price of servicing. To determine the actual price of servicing, a service provider would need to compute the customer's demand function based on the "true" maximum servicing price, determine the associated supply curve with respect to servicing, and determine the intersection of the two curves. The intersection of the two curves would represent the number of servicing missions that a customer would purchase and the actual price of servicing that a customer would pay – a traditional application of the classic supply and demand curves.

With the knowledge of the supply and demand curves for servicing, a service provider can begin to examine the effects that legal and political issues have on the creation of feasible OOS market. For instance, a service provider can expect that a tax will result in a decrease in the feasible range of servicing prices, thus making satellite servicing less attractive; while a subsidy would increase the range of servicing prices, making servicing more attractive. The remaining problem for the service provider is to understand the current legal questions that OOS creates and thus develop a servicer that takes into account the potential ramifications that government actions would have. Therefore, addressing only the technical and economic issue of on-orbit satellite servicing is not sufficient for the creation of a feasible servicing market. A satellite service provider must also be aware of the unanswered legal questions that surround satellite servicing and determine how future government actions can affect the creation of a feasible servicing market. It is the intention that this chapter will assist in alerting potential satellite service providers to the legal questions that can affect the creation of an on-orbit servicer, as well as reminding governments how their actions could result in the stifling of innovation and/or prevention of potential on-orbit satellite servicing infrastructures.

Chapter 9. Impacts and Conclusions

Is OOS a paradigm shift in satellite design
or is OOS just a solution looking for a problem?

This thesis examined the economic roadblocks in the development of on-orbit satellite servicing capabilities and developed a method for evaluating the economic viability of on-orbit satellite servicing. However, the thesis looks to answer a much larger fundamental question. That question is whether or not traditional monolithic satellite design has limited the value that the satellite market generates for the space industry? Thus, has the technology development S-curve for monolithic satellites reached its saturation point and if so can on-orbit satellite servicing be a design method that will allow the industry to jump to a new s-curve?

The goal of this thesis was to answer the question posed in Chapter 1, does a method of satellite design exist that addresses the access constraint of satellites while providing greater satellite performance and maintaining investor return. Based on the results provided in this thesis, the answer should be clear – yes; at least one method exists. Hopefully, it is clear that this method is on-orbit satellite servicing. To support this conclusion, it was stated that, if OOS could provide greater value than alternative design options, OOS could provide greater performance while maintaining investor return.

To prove that such a statement was true, on-orbit satellite servicing was examined in terms of a commercial service market. The market was divided into a customer and a provider viewpoint. Dividing the analysis allowed for the evaluation of both sides of the market to be performed independently. An on-orbit satellite servicing market was said to exist if, for a given amount of value, a common range of servicing prices existed for both the customer and the provider.

The first part of the analysis was to examine the customer side of the market. It was assumed that the goal of any customer was to maximize the value of the satellite. Therefore, a service provider would only service a customer's satellite if servicing provided greater value than all other options. To determine the value brought about by servicing, on-orbit satellite servicing was viewed as a way in which a customer could react to future uncertainty, i.e. as an option.

By using real options analysis, the additional value that OOS provided to the customer can be determined. The customer's maximum servicing price can be determined by finding the point at which the customer is indifferent to servicing (additional value = zero) versus the next most beneficial option. The customer's maximum servicing price then sets an initial range for common servicing prices for both sides of the market; Zero → Maximum servicing price.

In addition to determining the customer's maximum servicing price, critical information was gathered with regard to the characteristics of a feasible on-orbit satellite servicing market. This information is vital for service providers because these results direct a provider toward the design elements that have the greatest effect on creating a market. From the provider's point of view, the goal is to make the customer's maximum service prices as high as possible. By understanding how to affect customer value and the maximum servicing price, a provider can change the servicer design to maximize the customer's maximum servicing price and thus create a larger range of feasible servicing prices.

By performing sensitivity analysis on three example servicing scenarios, the following effects were found to affect the customer's maximum servicing price.

- The relationship between servicing price and value is not linear, even in the case of a commercial customer. It was found that due to the non-linear relationship between servicing price and customer value, slight variations in the servicing price around the maximum servicing price were only reflected as small changes in the customer's expected value. To produce a larger change in the expected value of servicing, a service provider must move away from the customer's maximum servicing prices and focus on lower, more attractive, servicing prices.

- Increasing the capability of the satellite through servicing has a proportional effect on the customer's maximum servicing price. Although only a linear relationship between unit-value increase and customer value were examined, it is expected that OOS will allow for significantly higher servicing prices if high correlations exist between the effect of new technology and customer value.

- Highly volatile markets provide the best case for servicing only when servicing will be the most valuable option for the customer. When other options exist that may provide more value to the customer, servicing is not the best option within highly volatile markets.

- Servicer risk has a uniformly decreasing effect on the customer maximum servicing price. As the risk of failure associated with the servicer increased, a customer would choose the option to service less often and as a result the expected value of the option decreased. Because the expected value of the option decreased, the customer's maximum servicing price decreased.

- Servicing is generally attractive to "risk-adverse" and "risk-neutral" decision makers and not to "risk-seeking" decision makers. This finding contradicts the general understanding that on-orbit satellite servicing is too risky for today's "risk-adverse" satellite industry.

- Fast-evolving technologies provide the most value to the customer. This supports the current belief that the value of OOS is its ability to incorporate new technologies earlier than is possible with traditional methods.

After the customer side of the market was analyzed, the next step was to focus on the provider side of the market. For the provider's side of the market, it is critical to understand that the design of the servicer is not dependent on the results of the customer side of the market. The purpose of the provider is to fulfill customer need for value. How the provider goes about fulfilling this need is up to the provider. Because the provider is not tied to a specific design, multiple forms of servicing can be used to meet a single customer need.

Each one of these potential forms of servicing has its own design elements, supporting economics, policy implications, etc. But each form of servicing has one thing in common— each form of servicing has a minimum servicing price. The minimum servicing price is the lowest price that a provider could charge for servicing. It is assumed that a provider would provide a servicer for any servicing price above the minimum servicing price. Therefore, the range of feasible servicing prices for the provider is bounded between the minimum servicing price and infinity.

By determining the customer's maximum servicing price and the provider's minimum servicing price, a range of feasible servicing prices can be determined. The customer's range is bounded by zero and the maximum servicing price and the provider's range is bounded by the minimum servicing price and infinity. Thus the feasible range of servicing prices consists of the servicing prices between the minimum servicing price and the maximum servicing price. It is within this range of servicing prices that a feasible on-orbit satellite servicing market exists. This range can be determined by overlaying the customer's maximum servicing price with the provider's minimum servicing price and looking for an overlap.

By creating this overlap, a higher level conclusion is discovered. The customer's maximum servicing price represents an "implied" demand curve and the provider's minimum servicing price represents an "implied" supply curve. The overlap of these two curves therefore creates an artificial representation of the classic microeconomic supply and demand curves. By comparing the curves in this manner, one can apply and determine the effects of classic microeconomic principles such as tax and subsidy.

The implied effect of a tax, discussed in Chapter 8, would be an increase in the minimum servicing price or a decrease in the maximum servicing price depending on who would be taxed. It was also discussed in Chapter 8 that, due to the current U.S. corporate tax laws, it is possible that a service provider would incorporate outside the United States in order to avoid U.S corporate tax. However, while this strategy has tax benefits, it also carries with it policy reactions such as export control restrictions. Therefore, avoiding corporate tax by moving off shore may not be the best idea for a service provider. What might be needed to keep service providers within the United States is for the U.S government to apply some tax-incentives on the first-movers in order to push innovation.

The development of on-orbit satellite servicing is not limited to solely economic and technical issues. OOS may create the first purely commercial space-based enterprise. Along with the development of an entirely new market come the legal issues, liability issues taxation issue, etc. The legal and political implications from the development of OOS remain unclear due to the fact that as of yet these areas of interest have yet to be tested. Therefore, for an OOS market to exist, the current legal and political policies of today's satellite industry will need to be updated.

Finally, it is the push for innovation that is lacking from the development of on-orbit satellite servicing. While many research programs are being conducted by a wide variety of industry players, what is lacking is government or industry incentives for technology development. A push for on-orbit technologies could be seen with a wide variety of incentives. For instance: on-orbit satellite servicing innovations could be pushed with the creation of tax breaks or government subsidies, the shift to a more modular and standardized satellite design, or finally the acceptance by the industry that uncertainty can generate value. Whichever one of these approaches is to be the best remains to be seen.

Thus, it is likely that these answers may only come to light once the first mover has entered into the market.

Despite the tangled web of economies, political, technical, and legal issues that are created by the development of a space-based market, OOS clearly addresses and resolves the issues of satellite access and delivery of additional value to the satellite operator while maintaining investor return. Therefore, OOS is not a solution looking for a problem, but is a shift in satellite design. What then is preventing the shift in satellites design towards serviceable satellites?

For OOS to bring about a paradigm shift in satellite design, OOS must revolutionize or transform the way satellites are designed. In addition to the revolutionary design, a paradigm shift requires that breakthroughs in thinking or capability result from the change. Based on this definition of paradigm shift, one could argue that, if a technology could be classified as a disruptive technology as according to Christensen (Christensen, 1997), that technology has the potential to produce a paradigm shift. Thus, does on-orbit satellite servicing meet Christensen's requirements for a disruptive technology and if so does it have the makings of a paradigm shift?

According to Christensen, a disruptive technology is a technology that brings to the market a very different value proposition than was previously available (Christensen, 1997). Based on Christensen's definition, on-orbit satellite servicing clearly represents a disruptive technology because it delivers value based on the customer's ability to react to future uncertainty. Not only does the ability to react to future uncertainty classify OOS as a disruptive technology, but also generating value by reacting to uncertainty is a shift in the space industry's thinking. The shift in thinking represents a paradigm shift in satellite design over traditional satellite design, which prevents the satellite from reacting to future uncertainty due to its design. Thus OOS not only represents a disruptive technology, but OOS leads the way towards a paradigm shift in the design and valuation of satellites.

OOS provides a means for escape from the traditional approach of satellite design, thereby allowing one to make a paradigm shift towards more valuable design approaches. OOS may be the new technology that allows satellite designers to escape from the technology s-curves described by Christensen (Christensen, 1997) and move towards new design methods, higher performance, and new technology s-curves. OOS represents a disruptive technology due to the fact that OOS creates a new valuation proposition for the satellite industry. With disruptive technologies come the opportunities for greater value and dramatic change. With OOS comes the opportunity for a paradigm shift in satellite design that can lead to dramatic new ideas, uses, and valuation of space. In conclusion: to promote the adoption of on-orbit satellite servicing by the satellite industry, today's satellite operators should focus on medium volatility markets, low risk servicing missions, and incorporate fast evolving technologies that result in significant increases in satellite value.

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