

On-Orbit Servicing For Satellite Upgrades

by

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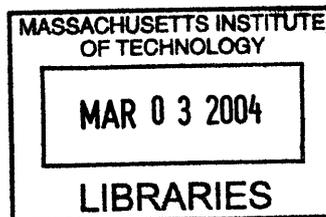
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Abstract

Except for manned servicing operations using the Shuttle, there is no maintenance infrastructure for space systems. The traditional approach is to build in reliability and to replace the system in case of obsolescence or failure. Space systems therefore offer a limited degree of flexibility to adapt to evolving conditions during their long design lifetimes. On-orbit servicing could change this paradigm by providing a physical access to the satellite after it has been deployed. Satellite upgrade appears as a very promising application. On-orbit servicing could offer a broader range of upgrades than current improvements through communication uploads and would be a cheaper alternative to satellite replacement.

The attractiveness of on-orbit servicing for satellite upgrade is investigated from a customer point of view. A dynamic framework, based on Real Options and Decision Tree Analysis, is used to account for the value of the flexibility offered by on-orbit servicing. Two case studies are developed: a power upgrade on-board a commercial geosynchronous communication satellite facing an uncertain demand and technology upgrades on a scientific observatory.

The power upgrade of a geosynchronous communication satellite is assumed to restore beginning of life power. The model shows that modifying the initial design of the satellite to compensate for power degradation is often preferred to on-orbit servicing because it offers a cheaper and less risky alternative. On-orbit servicing does not appear attractive in this case because the upgrade has a limited effect on satellite capacity and power degradation is a predictable phenomenon that can be partly overcome by design modifications.

Using the unique example of the Hubble Space Telescope servicing missions, the upgrade of the payload instruments and the bus subsystems on-board a scientific observatory is modelled. It is shown that satellite upgrades can significantly increase the utility of the mission, in particular if technology is evolving rapidly.

It can be concluded from these two case studies that on-orbit servicing is viable and attractive if the increase in utility due to the upgrade is sufficiently large and if there is no other alternative that can offer a similar increase in utility at a lower cost or lower risk.

Potential policy barriers to the acceptance of on-orbit servicing are identified and candidate policies are proposed to promote and enable the development of an on-orbit servicing infrastructure. A government intervention is likely to be necessary to overcome the risk averseness of the space industry and the "chicken and egg" problem arising from the necessity of designing the satellite for serviceability.

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Title: Professor of Aeronautics and Astronautics and Engineering Systems

Co-director, Engineering Systems Division

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Nomenclature

Roman

\mathcal{B}_{Act}	Actual revenues or demand
\mathcal{B}_F	Forecasted revenues or demand
\mathcal{C}	Cost function
C	Option price
C_i	Expected cash flow at time i
$C^{(i \rightarrow j)}$	Switching cost from state i to state j
C_{IOC}	Cost to initial operating capability
C_{op}	Operation cost function
C_{rep}	Repair cost
d	Discount rate or Scientific instrument generation
\mathcal{D}	Actual demand
\mathcal{D}_f	Forecasted demand
D_i	Decision i
dz	Increment of a Wiener process
$E[\dots]$	Expected value operator
EV	Expected value
$EV_{[T_k, T_H]}^{n \rightarrow m}$	Expected value over the period $[T_k, T_H]$ when a switch from state n to m is done at T_k
$EV_{[T_k, T_H]}^n$	Expected value over the period $[T_k, T_H]$ for an entry state n at T_k
FV	Flexibility value
$I_k^{n \rightarrow m}$	Set of values x_k for which a switch from state n to state m is optimal at T_k
InP	Indium Phosphide
L_d	Solar cell degradation coefficient

\mathcal{IR}_τ^m	Incremental revenues generated over a period τ according to the forecast
\mathcal{M}	Actual revenues for a commercial mission
\mathcal{M}_f	Forecasted revenues for a commercial mission
m_f	Failed system state
N	Maximum capacity of a communication satellite
N_B	Generation of the on-board bus technology
N_B^d	State of the art bus technology when an instrument d is invented
N^{ref}	Reference parameter to define the decrease in utility due to bus technology obsolescence
N_{user}	Number of simultaneous users the satellite can serve
o_p^m	Operation cost per unit time in state m
p	Real probability
P_{BOL}	Beginning of life power
P_f^R	Probability of failure of a replacement launch
P_f^{Serv}	Probability of failure of a servicing operation
P_{pay}	Power used to size the communication payload
P_S	Probability of success of the observatory operation
P_S^{Serv}	Probability of success of a servicing operation
$P_\$$	Price of a billable minute
q	Risk neutral probability
r	Risk free interest rate
\mathcal{R}	Revenue function
S	Market price of a stock
Si	Silicon
T_H	Time horizon for the valuation
T_B	Mean time between arrivals of new bus technologies
T_I	Mean time between arrivals of new instruments
T_k	Decision point k
t_{pay}	Time for sizing the communication payload
u^m	Utility rate per unit time in state m
u^d	Utility rate per unit time with the instrument d
u_m^d	Maximum utility rate per unit time with the instrument d
$var[...]$	Variance operator

V	Value function
V_B	Value of a baseline non-flexible mission
V_F	Value of a flexible mission
X	Uncertainty parameter
X_B	Stochastic variable representing the arrival of a new bus technology
X_I	Stochastic variable representing the arrival of a new instrument
X_k	Variable representing the value of the uncertainty parameter observed at T_k
x_k	Possible value of X_k
Y	Logarithm of the uncertainty parameter X

Greek

α	Drift of the Brownian Motion
ΔH_y	Step size characterizing the evolution of y in a binomial tree
ϵ	Random variable following a standard normal distribution
η	Factor of increase in forecasted revenues due to an upgrade
π	Profit
σ	Market volatility

Superscripts

+	Favorable market conditions
-	Unfavorable market conditions
*	Optimal strategy
n	System entry state at a decision point T_k
m	System end state at a decision point T_k
$n \mapsto m$	Switch from state n to state m

Acronyms

ACS	Advanced Camera for Surveys
AR&C	Autonomous Rendez-vous and Capture
BOL	Beginning of life
CERs	Cost Estimation Relations
COS	Cosmic Origins Spectrograph
COSTAR	Corrective Optics Space Telescope Axial Replacement
CSA	Canadian Space Agency
DARPA	Defense Advanced Research Projects Agency
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Space Agency)
DOD	Depth Of Discharge
DTA	Decision Tree Analysis
EOL	End of life
ESA	European Space Agency
FOC	Faint Object Camera
FOS	Faint Object Spectrometer
GEO	Geostationary Earth Orbit
GHRS	Goddard High Resolution Spectrograph
GPS	Global Positioning System
GSV	GEO Servicer Vehicle
HSP	High Speed Photometer
HST	Hubble Space Telescope
IOC	Initial Operating Capability
LEO	Low Earth Orbit
LST	Large Space Telescope
MF-CDMA	Multiple-Frequency Code Division Multiple Access
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NCC	NICMOS CryoCooler
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NPV	Net Present Value

OMV	Orbital Manoeuvring Vehicle
OOS	On-Orbit Servicing
QPSK	Quadriphase Phase Shift Keying
R/D	Rendez-vous/Docking servicer
SAMS	Space Assembly, Maintenance and Servicing
SLESTM	Spacecraft Life Extension System
SMAD	Spacecraft Modular Architecture Design for On-Orbit Servicing
SMM	Solar Maximum Mission
STIS	Space Telescope Imaging Spectrograph
TECSAS	TECHnology SATellite for demonstration and verification of Space systems
WFPC1	Wide Field Planetary Camera 1
WFPC2	Wide Field Planetary Camera 2
WFC3	Wide Field Camera 3

Chapter 1

Introduction

On-orbit servicing refers to the maintenance of space systems in orbit, such as the repair, refueling or upgrade of satellites after their deployment. On-orbit servicing could change the way space systems are designed and operated and is believed to offer great opportunities. Servicing missions have already been conducted by astronauts using the Space Shuttle. The Hubble Space Telescope mission, a unique example of an unmanned platform designed to be regularly serviced, illustrates the great benefits that can be gained by developing a maintenance infrastructure for space systems.

1.1 A successful example: the Hubble Space Telescope

In 1977, Congress approved funding for the most complex and ambitious space telescope: the Hubble Space Telescope (HST) was deployed on April 24 1990 by the Shuttle Discovery. The HST has looked at the universe and has provided crucial information to help understand the structure, the origin and the fate of our universe. More than 330,000 separate observations have been carried out and more than 25,000 astronomical targets have been observed. The extraordinary discoveries made with the HST were possible thanks to the revolutionary design of the telescope. A modular design has been adopted that allows astronauts to repair, maintain and upgrade the telescope. Three servicing missions have been performed to both repair and keep the telescope a state of the art observatory for the past 13 years. *“Hubble is the first scientific mission of any kind that is specifically designed for routine servicing by spacewalking astronauts. It has a visionary, modular design which allows the astronauts to take it apart, replace worn out equipment and upgrade instruments.*

These periodic service calls make sure that Hubble produces first-class science using cutting-edge technology. Each time a science instrument in Hubble is replaced, it increases Hubble scientific power by a factor of 10 or greater!”[24].

One of the most spectacular missions was the first servicing mission that aimed at repairing an optic flaw in the primary mirror that was causing every observations to be blurred. The HST would have been lost without this repair mission. The solar arrays and the gyroscopes were also replaced to maintain the health of the satellite. The Hubble Space Telescope is also an illustrative example of the benefits that can be gained from satellite upgrades. Many instruments were changed to take advantage of new technologies available allowing the scientific community to have an up to date telescope at a lower cost than if the spacecraft had to be replaced. New instruments installed during the second servicing mission in 1997 multiplied the spectral resolution and the spatial resolution of the imaging spectrographs by respectively 30 and 500. Additional solid state recorders were installed to increase the data storage capacity.

The HST example illustrates the advantages of having a serviceable satellite. Servicing operations allowed saving the mission and repairing the telescope for a lower cost than if the spacecraft had to be replaced. The cost of the first servicing mission amounted to \$500 million which is still lower than replacing the \$1 billion telescope. On-orbit servicing also offered the capability to adapt the system to new requirements, to take advantage of new technologies and to maximize scientific return by taking into account new discoveries and the evolution of knowledge.

The HST servicing missions require the intervention of astronauts and therefore are expensive operations that few space missions can afford. The total cost of the three servicing missions performed already exceeds the total cost of the initial observatory. However, it is a successful illustration of the potential benefits of on-orbit servicing for the repair and upgrade of satellites. The HST is a one of a kind example in today's space systems that are commonly not designed to be physically accessed after having been placed in orbit. If the cost of a servicing operation could be reduced enough to be affordable to most space missions, on-orbit servicing could create a new paradigm in space systems design.

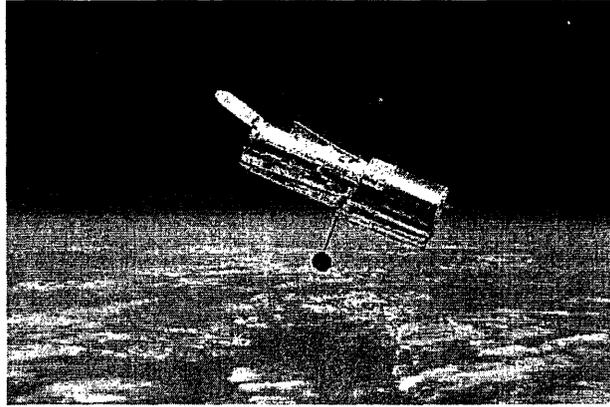


Figure 1-1: Photo of the Hubble Space Telescope (HST) in orbit.

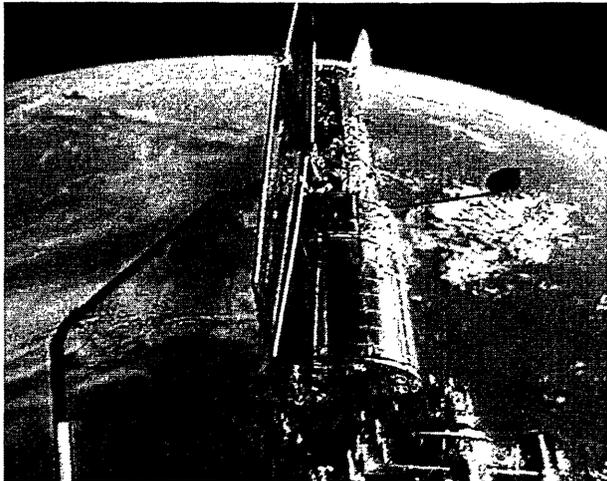
1.2 Current trends in space system design

Except for manned servicing operations using the Space Shuttle, no maintenance infrastructure exists to physically access a satellite in orbit. Manned operations are prohibitively expensive for most space missions except for large programs such as the Hubble Space Telescope or the International Space Station. Traditional satellites do not have access to the possibility of repair, refuel or upgrade. In case of failure or obsolescence, the only option offered to space operators is often to replace the satellite even if a large part of the satellite is still operational.

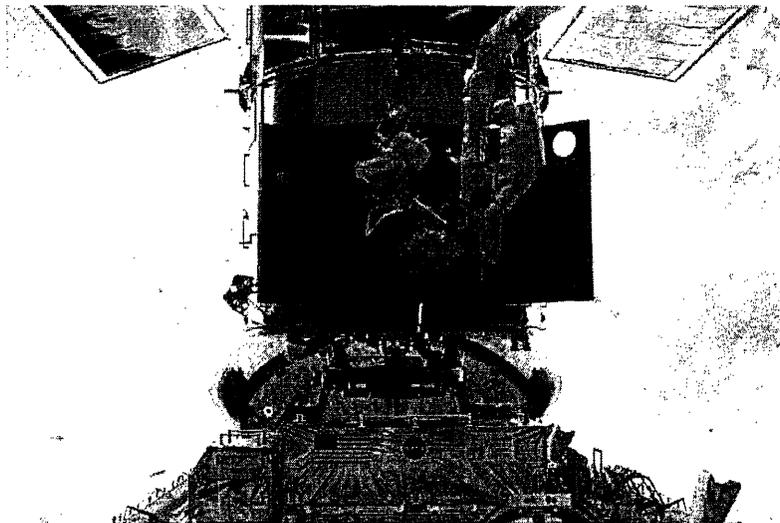
As a result, the current trends in space systems design are towards highly reliable, very expensive and non flexible satellites. Space systems are designed for relatively long lifetimes often exceeding a decade.

The initial cost of designing, building and launching a satellite is large compared to the operational cost. A long design lifetime reduces the cost per operational day and ensures a higher return on investment. Since no option to extend the life of the satellite is available, all subsystems on board must be designed for a long time of operation. Because of long design lifetimes and the absence of maintenance infrastructure, more fuel is carried on-board the satellite at launch, larger solar panels must be installed to produce the required power at end of life, highly reliable components are used and redundancy is added in the design. Therefore, long design lifetimes and reliability requirements contribute to increase the satellite cost and therefore the cost of replacing the system.

Moreover, there is no opportunity for space operators to physically access the satellite to



(a) Hubble Space Telescope captured by the arm of the Space Shuttle during servicing mission 3A of the HST.



(b) Extravehicular activity during servicing mission 3A of the HST.

Figure 1-2: Photos of the third servicing mission of the Hubble Space Telescope (servicing mission 3A) in 1999.

modify the system. Therefore, the capacity to react to potential modifications in the satellite environment, to adapt to modifications in requirements or to benefit from technology improvements are limited. This lack of flexibility makes satellites vulnerable to uncertainty and risk since the system cannot adapt to changes. Figure 1-3 illustrates four types of potential risk due to future uncertainty:

- *Risk of system failure:* The performance of the system over a long lifetime is uncertain and failures may occur. A common practice is to either build redundancy or very high reliability in the system to prevent a loss of performance resulting from a component failure, leading to added mass, complexity and therefore increased cost of the initial system.
- *Risk of technology obsolescence:* The time scale characterizing the evolution of technologies is likely to be smaller than the lifetime of the satellite. Technology obsolescence can have major consequences on the level of performance of the satellite: this in turn could cause threats to military assets or could, for commercial missions, translate to a loss of market share to competitors (satellites newly launched including the more advanced technology or new ways of completing the same mission cheaper).
- *Risk of commercial obsolescence:* For commercial missions, the dynamics of the market the satellite is serving is highly uncertain and no market evolution can be predicted 15 years in advance. Demand may drop or increase above predictions, the served market may not exist anymore or new markets may have emerged that the satellite is not able to serve.
- *Risk of change in customer requirements:* In general, customer desires may evolve over time. A rigid system will not be able to adapt to varying customer's requirements.

Some approaches have been investigated to add flexibility to space systems without physically accessing the system. Software upgrades are currently done through uploads using the satellite communication links. Studies have been carried out on flexible subsystems that allow reconfiguration in orbit or on satellite constellation reconfiguration. However, those methods are limited by the fact that the satellite cannot be physically accessed. Some software upgrades would require a change in computer hardware for compatibility and computing power requirements. Large satellite constellation reconfiguration (in particular when

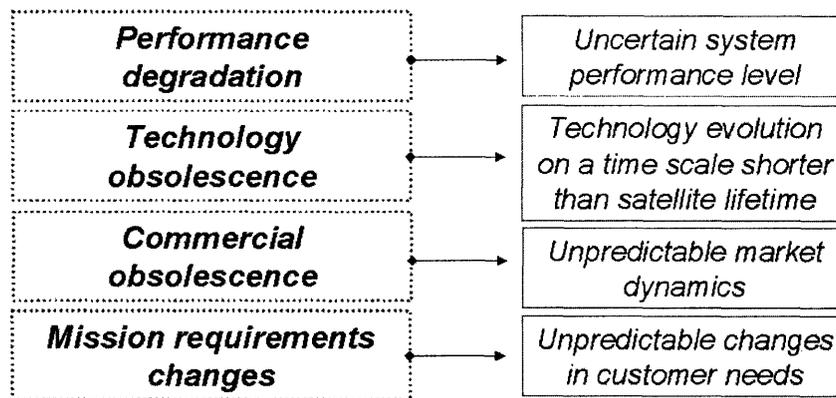


Figure 1-3: Potential sources of risk faced by space systems.

a plane change is considered) requires a large amount of fuel that is prohibitive if the fuel must be carried on-board the satellite at launch.

As a conclusion, current traditional satellites are very expensive systems designed for long lifetimes and that incorporate only a limited capacity to adapt to the environment uncertainty and the potential changes in mission objectives.

1.3 On-orbit servicing: a new paradigm for space systems design

On-orbit servicing, defined as a maintenance infrastructure for satellites in orbit, has been considered as a potential new paradigm in space systems design. By allowing to physically alter the satellite after it has been launched, on-orbit servicing would offer the possibility to repair, refuel or upgrade satellites. However, manned on-orbit servicing as done today on the HST or the International Space Station are prohibitively expensive and cannot be considered as a future routine on-orbit servicing structure. In order to drive the servicing cost down enough to make it affordable to most space missions, the idea of an autonomous on-orbit servicing infrastructure has been investigated. An unmanned satellite, called servicer, would rendez-vous with the satellite to be serviced, perform the repair, refuel or upgrade before separating and possibly conducting another servicing mission.

On-orbit servicing could provide both potential cost savings and an increased capacity to react to uncertainty. However, a satellite has to be initially designed to be serviced and the concept of serviceable satellites corresponds to a radical change in space systems design.

There is a cost associated to designing for serviceability and a risk associated to the servicing operation. In order to make on-orbit servicing the new paradigm in space systems design, the value of servicing must be demonstrated. What would be a reasonable cost that would make servicing attractive to traditional space missions? What are the conditions under which an on-orbit servicing infrastructure would be a valid concept? Technical aspects are not the only critical parameter in the development and the success of on-orbit servicing. Valuation studies must be done in parallel to technical and feasibility studies to answer those questions.

Some valuation studies have already been done that focus on estimating the cost savings realized with a serviceable satellite. However, the value of on-orbit servicing is not limited to the potential cost savings. The flexibility offered by on-orbit servicing has a value that must not be overlooked and must be estimated when carrying the evaluation of on-orbit servicing. The present work uses a new framework developed by Saleh [32] to capture the value of the flexibility.

1.4 Satellite upgrade

Satellite upgrade is considered as a promising application for on-orbit servicing for two main reasons. First, satellite upgrade offers an additional opportunity over satellite repair and refueling. The satellite performance is not only restored but can be increased or modified to better fit the needs of the user. Upgrading satellites offers a way to react against performance degradation, technological obsolescence or inadequacy with customer requirements. In addition, on-orbit servicing can be particularly attractive for satellite upgrade since it offers the opportunity to physically access the satellite and install new modules on-board the spacecraft. This broadens the scope of the upgrades that can be performed. In particular, new hardware using technologies that were not available at the time the satellite was designed can be added to increase the performance of the satellite. As an example, the on-board computer and the storage memory devices are considered very promising candidates for upgrade because the technologies used in these modules are evolving rapidly and can have a large impact on the capacity and value of the mission. Upgrades offer great opportunities when associated with a physical modification of the satellite.

However, upgrading a satellite during a servicing mission is very challenging. Physically

switching two modules on-board the satellite requires to have access to the satellite subsystems and to carefully manage the interfaces between the module and the other existing subsystems. The new module must be compatible with the pre-existing subsystems. In particular, the subsystems that are not designed to be upgraded constrain the scope of the upgrades that can be performed.

The benefits from satellite upgrade using on-orbit servicing seem very promising but many challenges are still ahead. A study of the value of on-orbit servicing for satellite upgrade appears as an important step in deciding on the potential attractiveness of the development of an on-orbit servicing infrastructure.

1.5 Thesis outline

As illustrated in the previous discussion, on-orbit servicing could radically change the way space systems are designed offering both potential cost savings and the benefits of increased flexibility to react to uncertainty. Because it represents such a large shift from current practices, the adoption of on-orbit servicing as the new design paradigm will require a careful study of the value of on-orbit servicing. The present study proposes to focus on satellite upgrade, which appears as one of the most promising applications of on-orbit servicing. The objectives are to determine for which conditions on-orbit servicing is attractive for satellite upgrade, to estimate the demand for satellite upgrade via on-orbit servicing and to get insights on what are the main drivers to the value of on-orbit servicing.

In Chapter 2, on-orbit servicing and satellite upgrade are discussed in more details. A brief review of the main past studies and the history of on-orbit servicing are presented to provide the context of this study. On-orbit servicing and satellite upgrade are then analyzed to derive the major characteristics that drive their value and the critical challenges that are potential hurdles in the future development of an on-orbit servicing infrastructure for satellite upgrade.

In Chapter 3, the valuation process is discussed. The concept of flexibility is first presented. Different valuation methods are then discussed from static valuation methods that fail to capture the value of flexibility to Decision Tree Analysis and Real Options Analysis that are better suited to take into account managerial flexibility. Finally the principles and building blocks of the framework used in the present work are explained.

In Chapter 4, the framework is applied to the specific case of the valuation of commercial space missions. A first example of the upgrade of a commercial mission facing uncertain revenues is developed.

In Chapter 5, a more detailed model of the upgrade of solar panels on a commercial GEO communication satellite facing an uncertain demand is presented.

In Chapter 6, the case of the technology upgrade on a scientific mission is studied. The model is based on the observations made from the Hubble Space Telescope mission. The upgrade of scientific instruments, the upgrade of bus subsystems as well as the repair of the satellite are included.

In Chapter 7, the policy aspects associated with the adoption of the on-orbit servicing concept are explored with the determination of the policy enablers and barriers to the development of an on-orbit servicing infrastructure.

Finally, some conclusions and recommendations for future analysis are summarized in Chapter 8.

From a provider's perspective

A classification of the on-orbit servicing operations have been given by Waltz [36] from the point of view of the operator providing the on-orbit servicing capability. Waltz identifies three classes of on-orbit operations depending on the type of operation the servicer must provide:

- **Assembly** refers to fitting parts together to build a complete or subsystems of a space structure. It can encompass deploying antennas or solar arrays for example. This operation is done before a system is fully operational.
- **Maintenance** operations, on the contrary, occur after a system has been deployed and aim at keeping a space system in an operational state. Waltz distinguishes preventive maintenance from corrective maintenance: the former regroups actions undergone before a failure occurs such as inspection, tests or repair/replacement of a unit before it fails; the latter corresponds to a maintenance operation in response to a system failure.
- **Servicing** includes all the operations to refuel or replenish a satellite in orbit.

From a customer's perspective

When adopting the point of view of a space operator willing to service a satellite, the on-orbit servicing operations may be classified quite differently, looking at their effect on the space mission. Saleh [32] proposes the following classification differentiating servicing operations along two dimensions: the performance of the system and the mission the system is carrying.

- **Life extension** deals with allowing the system to continue performing the same mission at the same level of performance. This can encompass repairing the system in case of a failure or refueling the satellite to keep the system operational.
- **System upgrade** regroups those operations that do not alter the original mission goals but aims at improving the operational system in meeting them.
- **A mission change** characterizes a maintenance operation that aims at modifying the mission the satellite was initially performing. Let's consider for example a commercial

Chapter 2

Satellite upgrade using on-orbit servicing

2.1 On-orbit servicing

Different methods can be used to upgrade a satellite. First, some upgrades can be done without any physical contact with the satellite and will be referred to as *non-physical techniques*. A common example is a software upgrade, which can be uploaded to the satellite computer system when the satellite is in view of one of the ground stations. Another example is the use of flexible subsystems in the initial design so that the satellite can be modified from the ground to adapt to some extent to modifications in requirements. An illustration of this concept is the use of communication beams that can be oriented to the zone of interest. A second alternative offered to space operators is to *launch a new satellite* to replace the obsolete or degraded satellite. A third option would be to develop a maintenance, or *on-orbit servicing*, infrastructure to physically access the satellite. We will present in this chapter an overview of the concept and the current status of on-orbit servicing.

2.1.1 Definition

On-orbit servicing can be defined as a maintenance infrastructure that offers the capability to inspect, repair, refuel, replenish and upgrade satellites in orbit. The particularity of on-orbit servicing is to offer a physical access to the satellite after it has been placed in orbit.

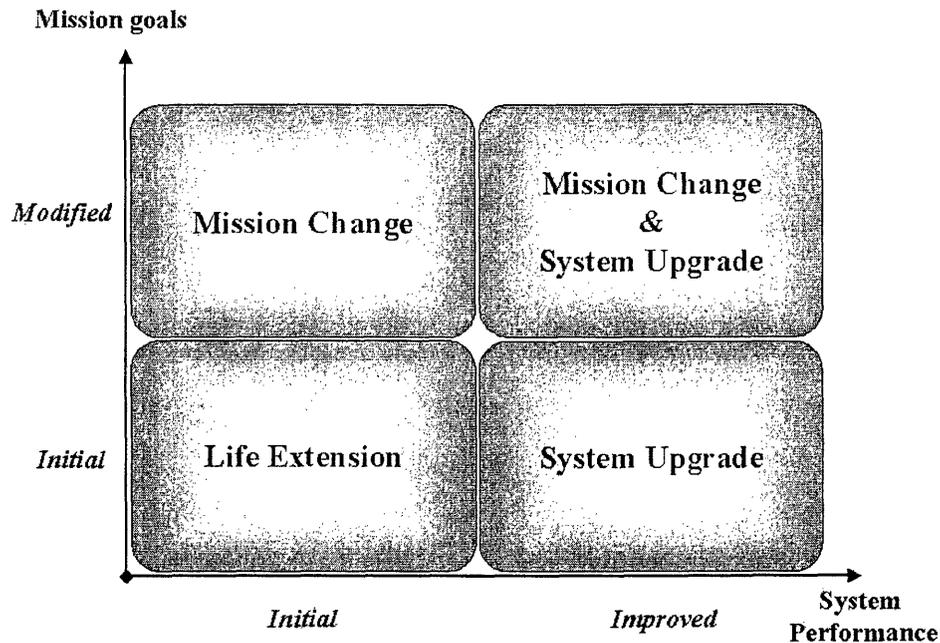


Figure 2-1: Characteristics of the different categories of maintenance operations along the two dimensions of system performance and mission goals [32].

mission initially designed to broadcast a television signal and transformed to be used to take pictures of the Earth. The intrinsic goal of the mission has been modified but the performance of the system is not necessarily changed.

Figure 2-1 illustrates the different categories of maintenance operations along the two dimensions of system performance and mission goals [32]. In the present work, we will adopt a customer's perspective and use the taxonomy developed by Saleh [32]. In particular, the term "servicing operation" will be used in a general sense to refer to any on-orbit servicing operation and not specifically for satellite refueling or replenishment.

2.1.2 On-orbit servicing architecture concepts

As discussed in the first chapter, on-orbit servicing has been done using humans in space. Manned servicing operations are still prohibitively expensive for most space missions and efforts have been made towards thinking about autonomous on-orbit servicing using robotic vehicles. Various concepts of autonomous on-orbit servicing architectures have been proposed ranging from a single vehicle to a large scale space based infrastructure.

Definitions

The following terms are used to describe on-orbit servicing operations and the different components of an on-orbit servicing architecture.

The **servicer** is the autonomous vehicle that performs an on-orbit servicing maintenance operation.

The **target** refers to the satellite to be serviced.

A **servicing operation** is a single maintenance item performed by a servicer on a target.

A **servicing mission** refers to the group of servicing operations accomplished by a servicer on a single target during one visit of the servicer to the target.

During a servicing operation, a new module may be installed by the servicer on the satellite and will be referred to as a **replacement unit**. It can be for example a new subsystem if the one on the original satellite has failed.

In the specific case of an upgrade, the replacement unit will be called an **upgrade unit** to distinguish it from other replacement units.

Space depots correspond to maintenance stations in orbit where replacement units, upgrade units or fuel can be stored.

Description of a servicing mission

The different steps in an autonomous on-orbit servicing mission are the following:

1. Engage servicing mission: The servicing mission is engaged either by launching a servicer or by activating a servicer already in orbit.
2. Approach the target: The servicer must then manoeuvre to get within proximity of the target.
3. Inspect the target: The servicer may inspect the satellite condition prior to docking.
4. Rendez-vous sequence and docking: The servicer will then engage the rendez-vous sequence to search and get within meters of the target before docking.
5. Servicing mission performed: The servicing operations are then performed by the autonomous servicer: refueling, installation of replacement or upgrade units.
6. Separation: The servicer then separates from the target.

7. End of servicing mission: At the end of the servicing mission, the servicer may be discarded or reused for another servicing mission.

An important characteristic is the timing of the servicing operation. A distinction must be made between servicing activities planned in advance, referred to as *scheduled operations*, and *on-demand operations* which correspond to unpredicted demand for a servicing operation as needed.

On-orbit servicing architecture variations

Different architectures have been explored and proposed for conducting autonomous on-orbit servicing.

First, the different infrastructures differ on the number of servicing missions performed by a servicer. The simplest concept considers that a servicer is designed to perform a single servicing mission on a specific target. However, this is not very cost efficient and other concepts have been proposed in which a servicer performs multiple servicing missions potentially on various targets.

A second characteristic is the status of the servicer before the servicing mission is engaged. The servicer can be launched as needed to perform the maintenance operations or the servicer can be placed before hand on a parking orbit from which it manoeuvres to the target as needed.

Finally, infrastructures proposed can vary in scope from a single vehicle that carries all the necessary parts to perform its mission to a large infrastructure including servicers and space depots. Parts, replacement units or fuel would be stored in space depots and regularly replenished. Servicers would get the elements necessary to their mission at the space depot before approaching the target to be serviced. Figure 2-2 shows an illustration of such an infrastructure as modelled by Nilchiani [27].

The most promising architecture highly depends on the maintenance operations performed. For example, in the case of the installation of up to date technologies, the potential advantages of storing the upgrade units in orbit in space depots must be traded against the resulting delay in the technologies that can be installed.

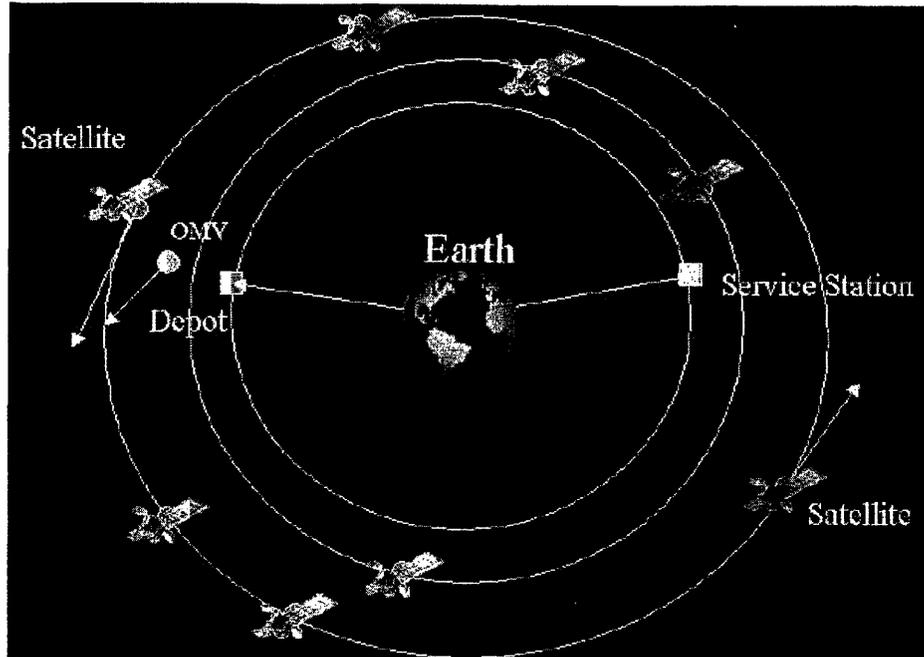


Figure 2-2: Example of a servicing infrastructure proposed by Nilchiani [27]. OMV refers to an Orbiting Manoeuvring Vehicle, which is close to the concept of a servicer in this work.

2.1.3 History of on-orbit servicing

After presenting an overview of the concept of on-orbit servicing, we will review past servicing missions and the past studies on servicing of space systems. Three main topics are addressed by past studies: 1) the servicing architecture and the servicer design, 2) the requirements for the serviced satellite and the impact of designing for serviceability and 3) the cost effectiveness of on-orbit servicing for various missions.

Manned servicing missions

The first maintenance operations in orbit were performed to repair, replenish or upgrade manned platforms such as the American space station Skylab or the Russian MIR station. Skylab maintenance activities such as the release of a solar array, the installation of a rate gyro package or the repair of a microwave antenna were all performed by astronauts. MIR used unmanned Progress vehicles to resupply the station and deliver cargo. The docking and refueling were performed automatically. Twelve Progress vehicles delivered more than 20 tons of equipment and the latest Progress-M vehicle performed more than 40 servicing missions demonstrating the concept of routine autonomous docking and refueling. More

recently, the International Space Station has been assembled and extensively maintained using the Shuttle. Supplies and cargo are regularly sent to the Station using the Progress vehicle and in the future the Automated Transfer Vehicle.

The first unmanned satellite to be serviced was the Solar Maximum Mission (SMM) following a failure of three of its momentum wheels and of its coronagraph instrument. Astronauts, launched on-board Shuttle Challenger, managed to repair the attitude control and the coronagraph electronic box to save the Solar Maximum Mission at a smaller cost than if the satellite had to be replaced. Other manned on-orbit servicing missions of unmanned satellites such as Syncom IV-3, were carried out using the Shuttle vehicle. Deployed on the second day of Shuttle mission 51-D, the Hugues Syncom IV-3 spacecraft failed when its booster stage did not fire as programmed. The satellite was repaired during a later Shuttle flight (Mission 51-I) allowing the satellite to be delivered to its GEO orbit.

The most extensively serviced mission was the Hubble Space Telescope (HST). The Hubble Space Telescope is the first unmanned spacecraft to be designed to be regularly serviced and boosted by the Shuttle. Immediately after its deployment, a major flaw in the primary mirror of the telescope was discovered causing all observations to be blurred. The first servicing mission corrected this aberration and saved the 1-billion dollar mission. Other servicing missions were conducted to repair but also upgrade the instruments and the other components of the spacecraft allowing the HST to still be a state of the art scientific instrument even after 10 years of operation. More details on the different operations conducted on the HST are described in Chapter 6.

Towards the development of an unmanned on-orbit servicing capability: cost effectiveness studies

Manned servicing operations were successfully conducted both on manned and unmanned platforms. However, the use of manned vehicles and astronauts in space make them very expensive operations that few space missions can afford. Studies have been conducted to investigate the concept of autonomous on-orbit servicing.

Space Assembly, Maintenance and Servicing (SAMS) project The 7-year SAMS project was conducted jointly by the Department of Defense, the strategic Defense Initiative Office and NASA. The objective of the study was to identify cost-effective goals for

an assembly, maintenance and servicing infrastructure towards more affordable and flexible space systems. Design reference missions were identified as potential servicing scenarios. In particular, the cost effectiveness of on-orbit servicing was investigated leading to some conclusions on the conditions for which on-orbit servicing is most valuable: when the replacement unit cost is lower than 50% of the replacement costs, when the servicing charges are lower than 50% of the replacement costs, when servicing time intervals are shorter than 4 to 5 years and shorter than a third of the time required to replace the satellite [16].

The Spacecraft Modular Architecture Design for On-Orbit Servicing (SMAD) study

The Spacecraft Modular Architecture Design for On-Orbit Servicing (SMAD) study was performed in 1996 by the Naval Research Laboratory [31]. The focus was to estimate the costs and benefits associated with the use of autonomous on-orbit servicing. This extensive and detailed work also made a significant contribution in understanding the design of servicing architectures and the impact of on-orbit servicing on satellite design.

Six potential benefits of on-orbit servicing were identified: a reduction in life cycle costs, an increase in the payload availability, an extension in the satellite lifetime, an enhancement of the space system capabilities and an increase in flexibility both during the mission and the pre-launch satellite integration.

Using the example of a remote sensing space system architecture, the SMAD study categorized different levels of on-orbit servicing. Components of the satellite were examined to analyze their potential replacement and it was concluded that approximately a third of all satellite components could be practically replaced and potentially many more if a modular satellite design were adopted. Modifications in satellite design were suggested to make space systems more compatible for servicing operations. The SMAD study introduced the concept of a **functional replacement** rather than a physical replacement. Failed components are not removed but instead are switched off. All the replacement components are assembled in a single replacement unit attached by the servicer to the satellite. The new replacement unit is switched on and performs the functions of the failed components. This strategy significantly simplifies the servicing operation, since a single module is plugged in by the servicer, therefore leading to a reduction in cost and risk.

A detailed design of an on-orbit servicer, called the Rendez-vous/Docking (R/D) Servicer, was developed in which the servicer can carry two replacement units. A bottoms-up costing

analysis was conducted combined with a Monte-Carlo simulation of the performance of the system. The study concluded that the proposed architecture could offer reductions in cost from 10.3% to 38.2% depending on the servicing scheme chosen.

Upgrade of GPS constellation An interesting contribution to the analysis of satellite upgrade using on-orbit servicing is the study of the upgrade of the Global Positioning System satellites. A first publication [13] investigated the design modifications that would be necessary to make the GPS satellite serviceable. A second study [19] considered on-orbit servicing as an alternative to the phased replacement strategy currently adopted for the GPS system. Different scenarios were derived by varying the servicing architecture characteristics and the maintenance/upgrade strategy followed. A metric was derived in close collaboration with GPS decision makers to score the performance of the different scenarios investigated. Six alternatives were recommended with the implementation of one servicer per plane. The selected alternatives may lead to higher costs than the current phased replacement strategy but also provide a higher level of utility to the decision makers based on the study metric. The study identifies on-orbit servicing as an opportunity to keep up with the technology evolution while designing satellites with long design lifetimes.

On-orbit servicing demonstration programs

Autonomous on-orbit servicing has been recently recognized as a promising concept and various efforts are underway to develop and prove the different stages for the development of a successful autonomous servicing infrastructure.

Various programs are developed by the European Space Agency (ESA), the German Space Agency (DLR), the Canadian Space Agency (CSA) and the National Space Development Agency of Japan (NASDA) both on technical challenges and on the economic and political impact of on-orbit servicing. ESA is analyzing a GEO Servicer Vehicle (GSV) to service satellites in the GEO belt. Cost estimations of the servicer as well as analysis of its mission have been developed [10] [39]. However, a demonstrator has not yet been built and tested because of financial constraints. The TECSAS (TEChnology SATellite for demonstration and verification of Space systems) is a program carried out by DLR to demonstrate key technologies for on-orbit servicing such as approach and rendez-vous techniques, capture mechanisms, stabilization and manoeuver of the compound target/servicer, manipulation

of the target and de-coupling of the compound. A workshop OOS (On-Orbit Servicing) is held every year by DLR, CSA and NASDA to discuss the future of on-orbit servicing. The ETS-VII program developed by NASDA aims at demonstrating the rendez-vous/docking phase between a target and a chaser satellite and unmanned space work conducted by tele-operation. The target is supposed to be cooperative and designed for docking.

The most extensive demonstration program is the Orbital Express program [9] sponsored by the Defense Advanced Research Projects Agency (DARPA). The program aims at designing, developing and testing in orbit a prototype servicer called ASTRO accompanied by a surrogate target serviceable satellite. ASTRO will conduct autonomous rendez-vous, inspection, docking, refueling and upgrade on-orbit. The program also aims at assessing the utility of on-orbit servicing for potential customers and at planning for technology transfer to facilitate the future development of a commercial on-orbit servicing infrastructure.

Life extension using Space Tugging

Advances have been done on space tugging of satellites, a concept close to on-orbit servicing. The tugger does not install any new hardware nor refuel the satellite in orbit but captures the spacecraft to control and move it. Various promising applications have been identified for space tugging such as transporting dead satellites to a graveyard orbit, performing the attitude control of satellites either to extend their lifetime or to reduce their fuel requirement or delivering satellites to their programmed orbit in case of a launch failure. A commercial company called Orbital Recovery Corporation is commercializing a space tugger called Geosynch Spacecraft Life Extension System (SLESTM) with the first mission targeted for a launch in 2004 for the rescue of the ASTRA 1K mission.

2.2 Satellite upgrade

2.2.1 Definition

As presented in the previous section, system upgrade is one of three categories of maintenance operations and is defined as the ability to improve the system operational performance in meeting its original mission. Two types of space system upgrades can be distinguished and will be discussed in the following paragraphs: the upgrade of a system of satellites and the upgrade of subsystems on-board a single satellite. The first concentrates on improv-

ing the overall capacity of the system without altering the individual performance of each satellite. The second focuses on changes within a satellite.

2.2.2 Upgrade of systems of satellites

Studies have been done on how to improve the overall performance or capacity of a system of satellites. The focus is not on modifying the individual satellites but to change the architecture of the system of satellites. This relates to reconfiguring the constellation, changing the altitudes or inclinations of the satellites or adding new satellites and growing the constellation.

The concept of staged deployment studied by Chaize and De Weck [5] at MIT is one example of such a system focused upgrade. Staged deployment refers to the concept of growing a constellation as necessary rather than directly designing the system for a full capacity.

Chaize examines the example of LEO communication constellations. In November 1988, the Iridium constellation was deployed and its 66 satellites launched in polar orbit. The system had been designed to serve a projected market of 3 million subscribers. By the time the Iridium service became operational, the communication market was radically different with the successful development of terrestrial cellular phones. With only 50,000 customers after thirteen months, Iridium had to file for bankruptcy.

A staged deployment strategy takes a different approach than the traditional design process: instead of designing the constellation for a full capacity (corresponding to the maximum capacity required to serve the prospective market over the satellite lifetime), the initial constellation is designed to serve a smaller market, closer to the initial market, and can then be expanded if demand is sufficient. The system therefore is grown as necessary depending on the market evolution. The aim of the design process is not to determine the optimum architecture to provide a given capacity but to identify a path along which the initial architecture can be grown if deemed necessary.

The main advantage of this concept is to offer the space operator a way to adapt to the uncertainty of the market: the space operator can protect against the risk of a bad evolution of the market while still being able to take advantage of a favorable evolution of the market. The challenges of this type of system oriented upgrades are mainly the reconfiguration process and the fuel and time necessary to reposition the satellites in a new configuration. However, no physical contact with or modification of the individual satellites is necessarily

required.

2.2.3 Upgrade of satellite subsystems

The present study does not consider the upgrade of systems of satellites but the modification of subsystems on-board an individual satellite. Three classes of upgrades have been identified as illustrated in Figure 2-3.

Upgrade against performance degradation

The space environment is harsh and as the time spent by the satellite in orbit increases, the performance of some subsystems may decrease. The solar panels, for example, are usually over-designed at beginning of life to ensure a required end of life power output. The performance of solar arrays degrades because of thermal cycling in and out of eclipses, micrometeoroid strikes, plume impingement from thrusters and material outgassing. The degradation depends on the type of solar cells used but can be as high as 3.75% per year for Silicon solar cells [37]. In this case, the upgrade consists in changing the degraded subsystem or refurbishing it to restore its initial or at least improve its level of performance. This type of mission is close to a repair mission in the sense that the performance is not increased from the initial operation of the subsystem. However, it is considered an upgrade mission because the degraded performance is not the result of a failure but a somewhat predictable evolution of the system.

Incorporation of new technologies

An upgrade operation may also aim at incorporating a new more efficient technology discovered after the satellite design was finalized. The lifetime of a satellite can be as long as 7 to 15 years. The time constants characterizing the evolution of the technologies embedded in the satellite are likely to be shorter than such satellite lifetimes. Typical examples of fast evolving technologies are softwares, computers, memory devices or scientific instruments. The new subsystems or products embedding the up to date technologies can significantly improve the performance and efficiency of the satellite in carrying its mission. Examples taken from the Hubble Space Telescope mission can illustrate the fast evolution of technologies compared to a satellite operational life. The new advanced computer installed on the Hubble Space Telescope in 1999 during Servicing Mission 3A was 20 times faster

than the previous on-board computer and had 6 times as much memory. The Advanced Camera for Surveys (ACS) installed on the HST in 2002 during the Servicing Mission 3B offered a discovery efficiency (product of field of view and instrument throughput) 10 times higher than previous cameras on-board.

Upgrade to adapt to changes in needs

The last category of upgrades identified relates to adapting the satellite to what the operator needs. The objectives of a space mission are almost always subject to some uncertainty. The required capacity for a commercial satellite will depend on the evolution of the market and demand which is difficult to predict with certainty 7 to 10 years in advance. Similarly to the concept of staged deployment, the capacity of a commercial satellite could be initially designed close to the observed demand at the beginning of the mission and then increased through upgrade operations if demand justifies it. The uncertainty in mission requirements is not limited to commercial missions. The requirements for a scientific mission may evolve as new discoveries are made, new knowledge is generated and new questions or hypothesis are raised. The requirements for a military mission may evolve depending on the location of the conflicts or political context. The concept of upgrading to adapt to evolving requirements is close to modifying the mission the satellite is serving and the distinction may seem unclear. A change in the mission the satellite is serving is considered as a major shift in the goals pursued whereas an upgrade to adapt to changes in mission requirements refer to small variations in the specific requirements within the same large mission goal. As such, for example, an increase in demand for a commercial mission is not considered a different mission but a variation of the initial mission due to inherent uncertainty.

2.3 Potential benefits of on-orbit servicing

On-orbit servicing offers a new approach to space system design by offering a maintenance infrastructure and therefore offering an alternative to designing satellites for longer lifetimes or for replacement. The attractiveness of on-orbit servicing depends on the comparison between the additional cost of designing for a longer lifetime and the cost of maintaining the satellite in orbit. Saleh [32] analyzed the impact of designing subsystems for a longer lifetime and concluded that the cost increases almost linearly with the design lifetime.

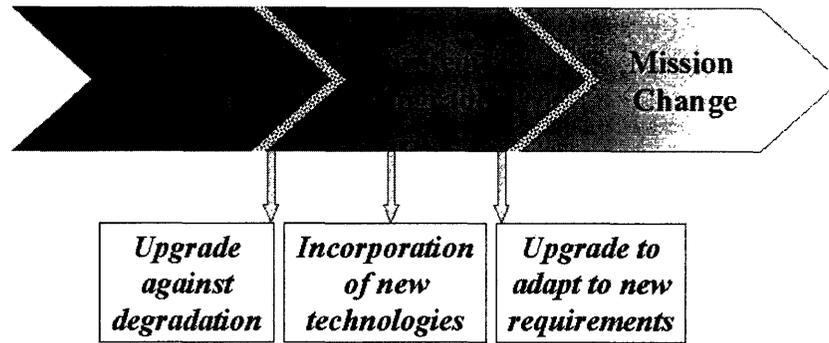


Figure 2-3: Different types of satellite upgrades.

Building in redundancy and using highly reliable components is a major source of cost in space systems. Many subsystems such as the batteries or the solar panels are over designed at beginning of life to ensure the required end of life performance after degradation. Additional fuel is necessary for station keeping. Therefore repairing and refueling satellites in orbit may offer potential cost savings in the initial satellite design.

It is considered that on-orbit servicing could change the way space systems are designed by offering a way to decouple *“the drive to lower satellites cost per operational day through extended design lifetimes from the ability to respond quickly to changing requirements and deploying new capabilities”*[34]. The trend towards longer design lifetimes is justified by the desire to reduce the cost per operational day. As a consequence the system must perform over a long period of time and therefore faces a large uncertainty for a non-flexible system. On-orbit servicing offers the space operator the opportunity to design the system for a long time of operation while having the possibility to adapt the system as its environment evolves.

On-orbit servicing can also allow new missions not previously viable. The reconfiguration of satellite constellations or the frequent manoeuvring of satellites are promising applications for refueling.

2.4 Technical challenges associated with the upgrade of satellites with on-orbit servicing

2.4.1 Challenges associated with on-orbit servicing

Autonomous on-orbit servicing of satellites requires the servicer to first rendez-vous and dock to the target and second to perform the maintenance or upgrade operation.

Autonomous rendez-vous and docking to cooperative spacecrafts have already been performed in particular in the context of the International Space Station. One of the most commonly accepted design is the autonomous rendez-vous and capture (AR&C) technology that allows docking with a passive target. However, current technologies first require the target to have attitude stabilization. Spin and gravity-gradient stabilized satellites cannot be serviced and in case of a failure of the attitude control subsystem, the servicer would not be able to dock with the target to carry out the repair mission. Second, current technologies assume that the target carries a docking interface that is not currently part of common satellite designs. Therefore, satellites currently in orbit that have not been designed to be serviced are not accessible with current technologies. Orbital Recovery Corporation is attempting to develop a docking technique that does not require a specific docking interface. The satellite kick apogee motor would be used as a point of attach to the target to tug the satellite.

Another technological challenge is the study of the dynamics of the combined target and servicer during the docking phase, of the docked configuration and during the separation of the servicer. Thermal management and structure analysis of the two satellite system is also considered a delicate stage.

A physical access to the target satellite is required to perform the maintenance operation. The most commonly proposed concept is a plug-in design with a functional replacement of the failed or upgraded components. Empty slots are introduced in the initial design of the target satellite with corresponding interfaces to the bus subsystems. If a failed component must be replaced or upgraded, a replacement unit is plugged in an empty slot, switched on to replace the old module and performs the function of the module replaced. This method has the advantage of not requiring the servicer to carry out complex operations when replacing the physical component to be serviced. Another proposed concept considers a design that allows the satellite to open up to give access to inside components. However

no precise study of this configuration has been proposed. A refueling mission is even more challenging since the fuel transfer must be controlled. It must be noted that all concepts require the satellite to be initially designed for serviceability and that the design choices in the initial satellite constrain the degree of flexibility. Various studies have been carried out on the impact of designing for serviceability. A study by the Aerospace Corporation [13] estimated the cost penalty to design for serviceability as an increase of about 10% in the total satellite mass. This estimate is based on the modification of an existing design for the GPS satellites.

Finally various programs focus on the development of robotic arms and control software to perform the servicing operation and install the replacement units. Different concepts are investigated from a complete autonomous operation to a teleoperated arm controlled from the ground through communication links.

2.4.2 Challenges associated with the upgrade of subsystems using on-orbit servicing

In addition to the challenges identified in the previous section concerning any servicing mission, technical challenges specific to an upgrade mission can be identified. One of the major issues of satellite upgrade is the compatibility of the upgrade unit with the subsystems initially embedded in the satellite. Power budget, data requirements, thermal management must be checked for as well as software compatibility. The subsystems not upgraded or not designed to be upgraded impose constraints on the scope of the upgrade that can be performed. These critical constraints are key to the value of upgrading while being difficult to estimate when modelling the upgrade of space systems. Other critical aspects of satellite upgrade have to be investigated such as interface management.

2.5 Critical criteria for the selection of on-orbit servicing

When comparing on-orbit servicing to non-physical upgrade methods or the replacement option, four main criteria can be identified that are critical to the selection of on-orbit servicing as the preferred solution to upgrade a satellite: cost, perceived and real risk, responsiveness and scope of the upgrade to be performed.

Non-physical methods Non-physical methods are the less expensive and less risky methods to upgrade a satellite. The risk is limited since there is no physical contact with the in-orbit satellite and no other satellite is launched. There is still the risk of the upgrade creating incompatibilities with the existing systems and potentially causing a catastrophic failure. The cost is reduced to a minimum with only the cost of the additional work at the ground stations. The upgrade can be implemented relatively rapidly and the time to upgrade only depends on the mission operator and the ground station personnel with no constraints linked to launch availability or orbit manoeuvring. However, the scope of the upgrade that can be performed is relatively limited. The first limitation relates to the constraints imposed by the compatibility with the systems embedded in the satellite. For example, software upgrades may at some point not be possible without upgrading the computer hardware as well. Moreover, since no physical modifications are done to the initial satellite, there is no possibility of implementing new hardware technologies or benefitting from new physical techniques discovered after the satellite design was finalized.

Satellite replacement On the other extreme, replacing the whole satellite allows the largest range of upgrade: new technologies can be incorporated and there are no constraints from other subsystems since all subsystems can be redesigned for compatibility. However, a replacement is an expensive solution. The whole satellite must be redesigned and launched even if only one subsystem is repaired or changed. Risk is the same as the risk of the initial mission, taking into account the risk of a launch and deployment failure and the risk of a failure during the beginning of the mission. It must be noted that a failure in the launch of the new satellite does not affect the former satellite that may still be operational.

Satellite servicing On-orbit servicing lies in between those two extremes. It allows physical modifications to be made to the satellite in orbit, therefore proposing a larger range of upgrades than non-physical methods. However, since the whole system is not modified, upgrades must be compatible with the on-board subsystems not upgraded. The range of possible upgrades therefore depends on how the satellite is initially designed for serviceability, in particular what modules are upgradeable and the number of upgrades that can be completed (for example the number of empty slots in a plug-in configuration). Choices in the initial design for serviceability must be made carefully because it constrains

the range of upgrades and modifications that can be realized later during the satellite lifetime.

Responsiveness depends mainly on the servicing architecture. If servicers are placed in orbit and parts stored in depots, no launch is necessary and the time to service can be shortened. If a launch is required either to place the servicer in orbit or to deliver the replacement unit to orbit, responsiveness will depend on launch availability and the time to get a servicer ready. For upgrade missions, storing upgrade modules in orbit to allow for a faster servicing operation also implies that the upgrade will not use the latest technology. The planning of servicing operations will also impact the responsiveness of on-orbit servicing. If a single servicer vehicle is used for multiple servicing operations, a delay may be incurred. However, it is likely that the on-orbit servicing method will be more reactive than the replacement option. The redesign effort only focuses on the specific subsystems to be upgraded and not on the whole satellite. The servicer vehicle will likely be smaller than the satellite to be serviced and therefore will be offered more launch opportunities reducing the launch delay. The total cost of an upgrade mission includes the cost of designing the upgrade unit to be placed on the satellite, the price of the servicing mission and additional costs such as insurance payments or increase in ground station operations. This cost is very uncertain because of the uncertainty around the cost of the servicing infrastructure but also because the actual cost of the servicing operation may not be the price charged to the user. If more than one space mission is visited by a single servicer, the price will be spread over the different users. Moreover, the price may be altered by policies implemented by governments to support or regulate on-orbit servicing.

Risk is another critical element in the value of on-orbit servicing. Upgrading a satellite using on-orbit servicing implies that the servicer will physically access the satellite and that the new module installed must be operating within the former set of subsystems initially in the satellite. These characteristics of on-orbit servicing create sources of risk in addition to the traditional failure modes that appear with the launch of a new satellite. A failure during the rendez-vous phase or when the servicer and the satellite to be serviced are in contact can be catastrophic. Moreover, some incompatibilities between the new hardware and the existing subsystems may appear and create a loss of the satellite functionality. Interface management is another important source of potential failure for on-orbit servicing.

Method	Non-Physical	On-Orbit Servicing	Replacement
Scope of Upgrade	Low	Medium	Unlimited
	-	New hardware technologies	-
	Constrained by embedded hardware No new hardware technologies	Constrained by non upgradable subsystems Determined by initial design for serviceability	-
Responsiveness	High	Uncertain	Low
	Depends only on ground station operations	Design/launch replacement unit only	-
	-	Depends on servicing architecture	Long design time for new sat Launch availability
Cost	Low	Uncertain	High
	Increase in ground station operations only	Potentially lower than redesign/launch new sat	-
	-	Cost of new module Price of servicing operation Depends on servicing architecture and policies	New satellite design New launch costs
Risk	Limited	Uncertain	Similar to initial launch
	Reduced because no physical contact Risk of incompatibility Error in new software	- Risk when physically accessing satellite Incompatibilities with existing subsystems Interface issues Depends on servicing architecture	Reduced risk of incompatibilities -

Table 2.1: Comparison of the three different upgrade methods.

Chapter 3

Valuation framework and flexibility value

The success of the development of an on-orbit servicing infrastructure does not only rely on resolving technical challenges. On-orbit servicing requires a change in the way space systems are designed and operated. In order to convince the space community, the intrinsic value of this new paradigm must be demonstrated. Therefore it is not only a question of “How to do on-orbit servicing?” but also “Is on-orbit servicing worth it?”. There are many sources of uncertainty in evaluating on-orbit servicing such as uncertainty in the cost of the infrastructure, in the design and cost of the servicer or some technical challenges that increase the perceived risk for space operators.

Cost-effectiveness studies have been conducted to estimate the value of on-orbit servicing for various missions. Their conclusions have indicated potential significant savings up to 40%. However, these encouraging savings were not considered sufficient to overcome the perceived risk and uncertainty in the cost and performance of on-orbit servicing.

Lamassoure and Saleh [33] identified two major limitations of traditional cost-effectiveness studies and proposed a new framework that aims at giving more general insights in the value of on-orbit servicing and at capturing the value of flexibility.

First traditional evaluation methods used in past studies are reviewed and their limitations are highlighted. Second, the concept of flexibility is discussed before describing different valuation methods to account for the value of flexibility. Finally, we introduce the framework chosen for the study, that has first been proposed by Saleh [33].

3.1 Limits of traditional cost effectiveness studies

3.1.1 Past cost effectiveness studies

Two main cost effectiveness studies have been presented in Section 2.1.3 in Chapter 2: the SMAD study and the upgrade of the GPS constellation. Traditional valuation methods usually focus on a specific mission of interest and compare potential cost savings from on-orbit servicing with the price of servicing. Figure 3-1 illustrates the usual process followed by past cost-effectiveness studies. A mission of interest is selected for the study and the desirable levels of maintenance are determined as potential servicing missions. Various candidate on-orbit servicing architectures are developed and evaluated. The cost of using on-orbit servicing is calculated as the sum of the cost of developing the selected servicing infrastructure and the cost of the design modifications necessary to make the target satellite serviceable. The cost incurred by on-orbit servicing are then compared to the benefits considered as cost savings from the baseline scenarios when the satellite is not maintained or replaced. Past studies have usually used traditional valuation methods such as the Net Present Value (NPV) to determine whether on-orbit servicing was cost effective or not. Past studies have often concluded that on-orbit servicing could potentially offer significant cost savings. However, it is considered that these conclusions do not offset the risk and uncertainty associated by space operators with on-orbit servicing.

3.1.2 Limitations of traditional cost effectiveness studies

Lamassoure [16] and Saleh [32] analyzed the traditional valuation process and identified four main limitations to the approach followed in past studies.

Mission specific/Service architecture specific results

The first step in traditional valuations is to choose a mission of interest and to design a corresponding servicing architecture. If this approach has the advantage of allowing more detailed estimations of the cost and performance of the servicing missions, it also lead to conclusions that are specific to some degree to the design choices and technologies selected for the servicing architecture. The cost of the servicing infrastructure highly depends on the architecture chosen (number of servicers, space depots...), the orbital characteristics and the servicer design, in particular the propulsion system chosen. It is therefore difficult to obtain

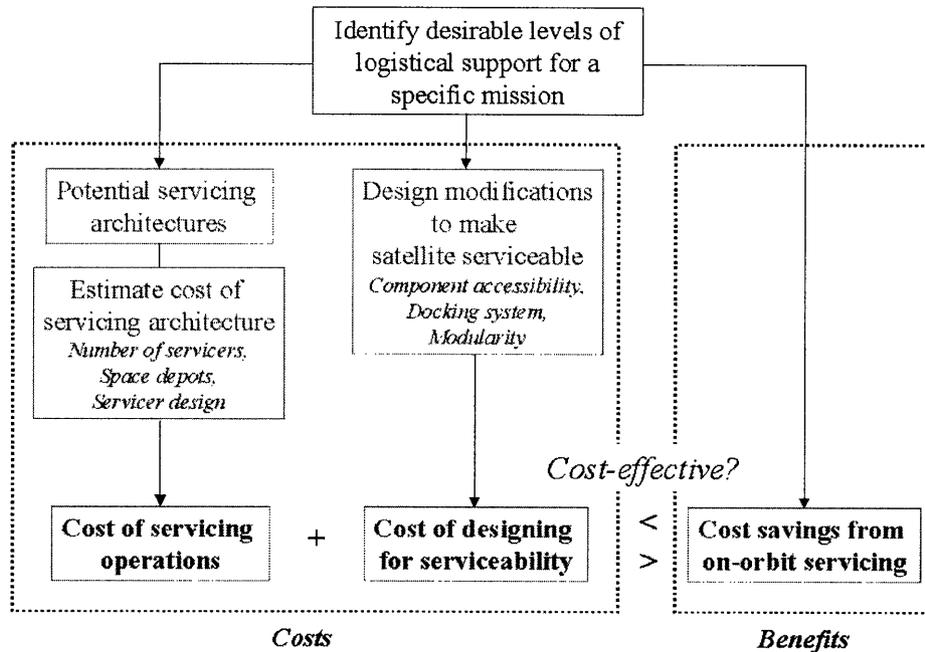


Figure 3-1: Usual process followed by past cost-effectiveness studies (inspired from [32]).

general insights on the intrinsic value of on-orbit servicing. As a way to address this issue, Lamassoure [16] proposed to describe the entire trade space of on-orbit servicing and explore methodically the entire set of missions and architectures. She identifies six main types of potential destinations, as shown in Table 3.1, and five different types of architecture, as shown in Table 3.2, to describe the trade space for on-orbit servicing. Cost effectiveness is evaluated across the trade space using standard Cost Estimation Relations (CERs) to estimate costs and a Markov model to take into account satellite and servicing failures. Applying the model to the particular example of Low Earth Orbit (LEO) communication constellations, Lamassoure concludes that even if there are some cases in which on-orbit servicing makes sense, the cost advantage is still smaller than the cost uncertainty and therefore the results are not convincing.

Cost uncertainty

Past cost effectiveness studies rely on the estimation of the cost of developing the servicing infrastructure and of conducting the servicing missions. On-orbit servicing has not yet been developed and therefore there is a high uncertainty on the costs associated with this concept.

Mission Type	Promising characteristics
High Value Asset	ex: International Space Station
	Replacement cost is so high than even manned on-orbit servicing is cost effective
New Missions	ex: Manoeuvrable military radar constellations using refueling
	On-orbit servicing enables new missions
LEO constellations	ex: Iridium, Globalstar
	Opportunity to amortize fixed cost of servicing on a large number of satellites
GEO satellites	ex: GEO communication satellite
	Expensive to replace
Whole GEO ring	-
	Highly populated orbit Incremental velocity to manoeuvre between satellites reduced because all satellites have same altitude and inclination
Several missions in several orbital planes	-
	On the basis that on-orbit servicing can only be viable on a large scale each mission only paying the marginal cost of servicing

Table 3.1: Six types of missions to describe the trade space for on-orbit servicing [16].

Maintenance Architecture	Characteristics
No on-orbit servicing	Baseline: only replacement option available
Disposal servicer carrying all cargo	Servicer launched with replacement unit
Satellites travel to depot/station	Satellites to be serviced manoeuvre to maintenance stations
Servicer travels	Servicers travel between maintenance stations and target satellites
Refuelable servicers	Same as previous but servicers are refuelable

Table 3.2: Five maintenance architectures to describe the trade space for on-orbit servicing [16].

First, on-orbit servicing will rely on some new technologies for which it may be hard to predict costs with confidence. Second, Cost Estimation Relations (CERs) are traditionally used to get an estimation of the costs of an infrastructure. CERs use historical data on satellite costs to model the sensitivity of costs to various design parameters. It is likely that a servicer will differ largely from conventional satellites and therefore standard CERs may not be directly applicable. Cost effectiveness studies compare the on-orbit servicing option with other scenarios. The uncertainty in estimating the cost of a servicer affects only the on-orbit servicing option and therefore is of significant importance when interpreting the results. Finally, the standard deviation associated with CERs often leads to cost uncertainties that are larger than the cost advantages estimated for on-orbit servicing and no conclusive statement can be made.

Price and cost of on-orbit servicing may differ

In the traditional process, the total cost of the servicing architecture is compared with the life cycle cost of the space system. However, it must be noted that the price a customer will pay for a servicing mission will likely be different from the cost of the servicing architecture. The price will reflect both the servicing provider's strategy and potentially government policies. It seems unreasonable to assume that a servicing infrastructure will be amortized over a single servicing mission or by servicing a single target. Each customer would pay only part of the large cost of the whole servicing infrastructure. Moreover, governments may decide to implement policies to support and accelerate the use of on-orbit servicing by subsidizing servicing providers. An infrastructure could even be entirely developed with government funding, the customers begin charged only the marginal cost of a servicing mission. Assuming that the whole cost of the servicing architecture must be amortized when looking at a specific mission is therefore highly questionable.

Traditional valuations do not take into account the value of the flexibility provided by on-orbit servicing

Traditional methods have been focusing on the potential cost savings that can be realized with on-orbit servicing. By adopting this point of view, an important component of the value of on-orbit servicing is overlooked: on-orbit servicing provides space operators with options to react to the resolution of uncertainty. The benefit of servicing for a customer

is not limited to cost savings but includes the new opportunities offered by this flexibility. The concept of flexibility and its value will be explained in more details in the next section.

3.2 Flexibility

3.2.1 Definition of flexibility

Flexibility has been used in various contexts and is often an ambiguous term. Saleh in his doctoral thesis [32] defines flexibility as:

“the ability of a system to adapt and respond to changes occurring after the system is in operation in a timely and cost effective way.”

Flexibility is linked to the capacity to adapt to changes in the system’s objectives or environment. Other words are commonly used in the context of performing in an uncertain environment and it can be useful to compare these different concepts to better capture the particularities of flexibility.

A first expression often used in software is **universality**. A system is universal if it can be used in different contexts without being altered. Flexibility, on the contrary, characterizes the fact that the system *can* be altered easily to adapt to modifications in the environment. Another word commonly used in design processes is the concept of **robustness**. A robust design refers to a system designed to be able to maintain the same level of performance in a varying environment. Both flexibility and robustness deal with a system in an uncertain environment. However, there is a major distinction between these two concepts: a flexible system can also adapt to changes in the system’s objectives and requirements whereas a robust system is by definition designed to ensure the performance of a system in meeting initial fixed requirements. Figure 3-2 illustrates the applicability of robustness and flexibility to characterize systems depending on whether they can react to changes in the system’s objectives and environment [32]. The subtle distinction between flexibility and robustness are well explained by Ku [15]:

“ Flexibility means the ability to change by quickly moving to a different state, selecting a new alternative or switching to a different production level. Robustness on the other hand is associated with not needing change. While flexibility

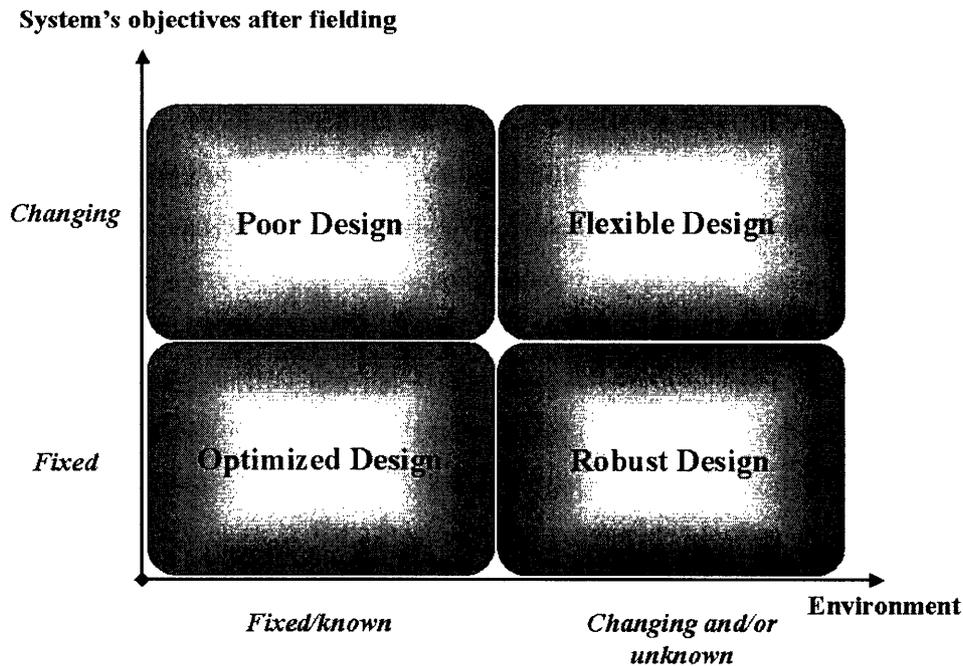


Figure 3-2: Distinctions between flexibility and robustness described with respect to the system's objectives and the environment the system is facing [32].

is a state of readiness, robustness is a state of being. Flexibility and robustness are not opposite or the same, but two sides of the same coin, two ways of responding to uncertainty.”

Robustness and flexibility illustrate two different strategies in dealing with uncertainty. A robust design tries to shield against uncertainty: designers will try to identify potential uncertainties and forecast the range of variation of the uncertainty parameters to make the system operational independently from the parameters' variations. Flexibility does not try to shield against uncertainty but acknowledges that uncertainty exists and looks for ways to adapt to unforeseen outcomes.

3.2.2 Flexibility value

As defined, it appears clear that in a world of certainty, flexibility has no value since the system can be designed and optimized for the known conditions that are to occur. However, if future conditions are uncertain, having the capability to adapt can have a significant value.

A mission is facing uncertainty if the evolution of one or more of the parameters essential to the mission cannot be predicted with precision. Uncertainty is often considered synonymous with risk, however they must be distinguished as different concepts. Risk refers to the particular case for which uncertainty leads to negative outcomes. For a fixed system that has been designed for given requirements and cannot be modified, uncertainty is effectively synonymous with risk. The system cannot adapt and therefore will be suboptimal if conditions are not what the system was designed for. Incorporating flexibility in a system allows decoupling uncertainty and risk since the system can be tailored to follow the evolution of the uncertainty parameters. Flexibility is useful in two distinct ways as illustrated in Figure 3-3:

- Managers can modify the system to **protect partially against risk**: if the resolution of the uncertainty parameter may lead to bad outcomes, the system can be altered to limit losses.
- However, flexibility is not limited to the role of an insurance. Flexibility can also **transform uncertainty into new opportunities**. The evolution of the uncertainty parameter may lead to good outcomes that could offer increased benefits. However, the system may need to be modified to be able to take advantage of these potential benefits. On the contrary of fixed systems, a flexible system will be able to take full or partial advantage of these opportunities.

Flexibility can be characterized as a **way to give managers the option but not the obligation to modify the system if it is optimal to do so**. The concept of options is essential to understand how flexibility adds value to the mission. Managers have the opportunity to alter the system after it is in operation therefore they can differ some decisions about the system to a later time when they have more information about the resolution of uncertainty. Flexibility adds value because better decisions can be taken as more information is available.

Flexibility value can be illustrated with the simple example of a commercial space mission facing uncertain demand. A fixed system corresponds to a system that has a fixed capacity and no opportunity to modify this capacity. A flexible system corresponds to a system that can be upgraded to increase its capacity if deemed profitable. A fixed system is incapable of adapting to the level of demand: if demand is low, operators will bear losses,

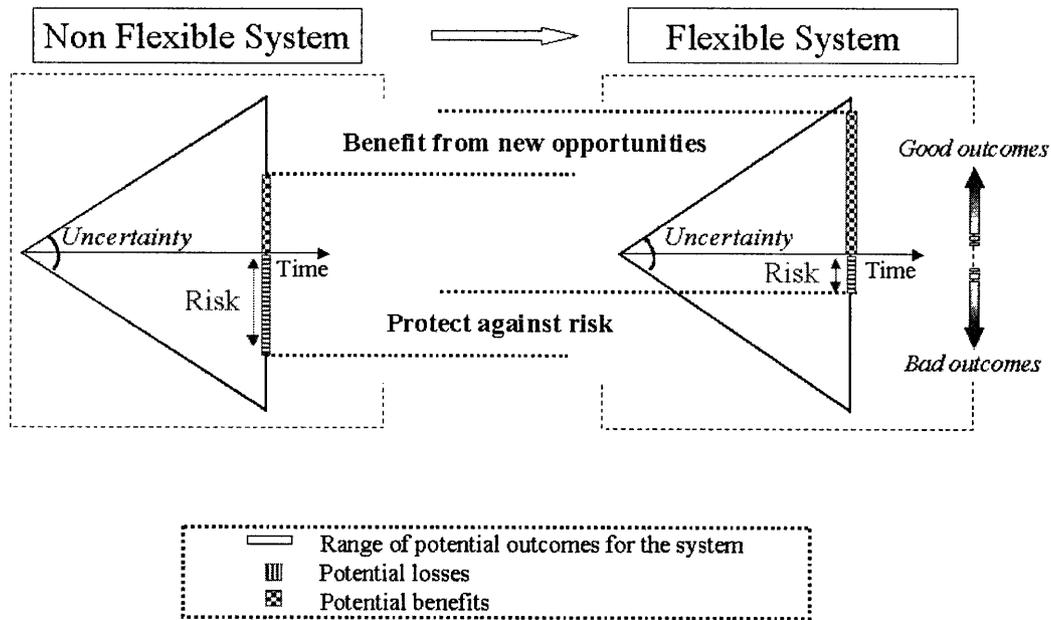


Figure 3-3: Flexibility and uncertainty. Inspired from [2].

if demand grows above the system capacity, operators will not be able to take advantage of these potential benefits. On the contrary, a flexible system can be designed for a lower capacity to limit losses in case of a low demand. If demand increases enough to justify the cost of an upgrade, the capacity of the system can be increased to take advantage of the benefits offered by the high level of demand. Decisions about the capacity of the system can be taken later in the system lifetime, when more information is known about the level of demand actually observed. Instead of deciding at the time of launch on the best system capacity to serve the market for the next 10 years, managers can adapt as they gather more information on the actual dynamic of the market.

The value of flexibility is often defined in comparison to a baseline system that does not offer this flexibility. The value of flexibility is the difference between the value of a flexible system and the value of the baseline system facing the same uncertainty.

3.2.3 Added flexibility offered by on-orbit servicing

Space missions are already flexible to some extent and benefit from some options:

Abandon option Space operators have the option to abandon the mission if the operational costs exceed the threshold at which the mission is considered viable.

Replacement option It is also common practice to replace satellites in case of failure, at end of life or to incorporate new technologies or capabilities.

However, on-orbit servicing has the potential to provide space operators with additional options increasing space systems flexibility:

Option to service for life extension One of the first aims of an on-orbit servicing infrastructure is to offer the opportunity to repair or refuel satellites in orbit. This encompasses the repair of random component failures, the refueling of satellites at end of life as well as the salvage of satellites launched in the wrong orbit that can manoeuvre back to their expected orbit after refueling.

Option to upgrade This option, which is the focus of the present work, offers the opportunity to restore a degraded performance, incorporate new technologies or adapt to changes in requirements.

Option to modify the original mission On-orbit servicing can even offer space operators the opportunity to modify the mission the satellite was initially designed for and to address new requirements.

3.3 Valuation techniques and flexibility value

Different valuation techniques are available to conduct cost effectiveness studies. Three different methods are reviewed in this section: the traditional Net Present Value (NPV) method, the decision analysis approach and the real option theory. The advantages and limitations of each methods are presented. In particular, it is shown that the NPV method, usually used in past cost effectiveness studies, fails to capture the value of flexibility. Decision Tree Analysis and Real Options Analysis are better suited to take into account the value of the options offered by on-orbit servicing.

3.3.1 Traditional static valuation technique: Net Present Value (NPV)

As it has been stated, most traditional cost effectiveness studies have failed to capture the value offered by the additional flexibility because they do not take into account the

fact that managers take rational decisions based on the information available at the time of the decision. Most past studies consider a predetermined sequence of decisions and then evaluate the resulting costs and benefits. Traditional valuation techniques such as Net Present Value (NPV) are used to conduct the cost effectiveness study. The NPV method is first presented before examining the limitations of this traditional valuation method.

Presentation of the Net Present Value method

The Net Present Value method is the most widely used valuation method as an investment decision tool. The principle of the NPV method is to look at the expected cash flows generated from the project and compare the sum of all cash receipts with the sum of all expenditures. Because of the time value of money, cash flows must be discounted to a common reference date using an appropriate discount rate. The discount rate depends on the project evaluated and must be taken equal to the rate of return of equivalent alternatives in the market place, equivalent referring to projects with similar cash flows and a similar level of risk.

A fixed discrete sequence of expected cash flows C_i is determined over the lifetime of the project and the Net Present Value NPV of the project is calculated as the sum of the discounted cash flows:

$$NPV = \sum_{i=1}^N \frac{C_i}{(1+d)^i} \quad (3.1)$$

where C_i represents the cash flow occurring at period i , N the total number of periods considered for the evaluation and d the discount rate. C_i is positive (respectively negative) for a net profit (respectively net loss) over period i .

The decision to invest or not in a project is based on the NPV rule: a manager should invest in a project if its NPV is positive and should discard the project if its NPV is negative.

$$NPV > 0 \iff \text{Invest in the project} \quad (3.2)$$

When comparing different projects, the project with the highest Net Present Value should be chosen.

If there is uncertainty about the future stream of cash flows, the expected value of the cash flows is used in the NPV calculation.

Advantages of the Net Present Value method

The NPV method is easy to use and straightforward to understand or explain to decision makers. It allows comparing different projects by only looking at the cash flow streams generated by the investments. Moreover, the Net Present Value rule can be easily generalized for non monetary values. For some missions such as some scientific or military missions, the benefits gained from a project are not expressed in dollar amounts. In this case, the benefits are measured by a utility metric that characterizes the performance of the mission. The logic of the NPV method can still be used by comparing discounted costs with the utility provided, using decision metrics such as $\frac{Utility}{Discounted\ Cost}$.

Limitations of the Net Present Value method

The Net Present Value method presents two main limitations when considering a system in an uncertain environment. First, the adequate value to be chosen for the discount rate is very hard to determine while driving the value of the project. Second, the NPV method considers a fixed sequence of cash flows and therefore does not account for the value of the flexibility.

The choice of an adequate discount rate is source of much debate and is a key driver of the valuation. If the project leads to sure cash flows, the risk free rate captures exactly the time value of money: an alternative would be to invest in Treasury Bonds for example. However, if the project is risky, the rate of return demanded by investors will be higher than the risk free rate otherwise investors could invest their capital in Treasury Bonds and get a higher certain return. The difference between the discount rate d and the risk free rate r is the risk premium. This risk premium depends on the level and the nature of the risk and is very hard to evaluate. The impact of the discount rate on the NPV is large and small variations in the discount rate may lead to different optimal decisions.

Moreover, it must be noted that the NPV method only considers a *fixed* sequence of cash flows. If there is no flexibility embedded in the system, the manager has to decide on a course of action at the time the system is fielded. This fixed strategy is used to conduct the NPV valuation. However, if the system is flexible, the manager has the option to take decisions later depending on the uncertainty resolution and on the information he has gained. Since the NPV valuation relies on a fixed sequence of decisions and resulting cash

flows, it fails to account for the value of the flexibility to adapt to uncertainty as it resolves.

3.3.2 Capturing the value of flexibility

In this section, two other valuation methods more suited to capture the value of flexibility are presented: Decision Tree Analysis (DTA) and Real Options Analysis. Decision Tree Analysis represents all possible scenarios taking into account potential values of the uncertainty parameter and the set of decisions that managers can take. From this, an optimal dynamic strategy is determined and the value of the project is calculated based on this strategy. Real Options Analysis adopts a different point of view and values options in relation with financial traded assets.

Decision Tree Analysis

Representation of the potential scenarios: construction of the decision tree

Flexibility is the possibility to modify the system to react to uncertainty. Decision Tree Analysis captures flexibility by representing this process as a discrete succession of uncertainty evolutions followed by decisions made by managers in reaction to this uncertainty resolution. All the potential combinations of decisions and evolutions of uncertainty are pictured in a decision tree.

The tree is constructed with branches and nodes. Branches start at a node and end at a node. The set of branches starting at a single node represents the different alternatives that may occur after this node. Nodes represent an alternative at a point in time. There are two types of nodes:

- **Decision nodes:** A decision node represents a point in time at which a decision maker is asked to make a decision. The set of branches leaving a decision node represents the different possible decisions available.
- **Chance nodes:** A chance node is a point representing an evolution of uncertainty. The set of branches leaving a chance node represents all the possible values taken by the uncertainty parameter at that point in time. All events from a chance nodes are independent. A probability is associated with each branch characterizing the probability of occurrence of this event. Since all events issued from a chance node are

independent and completely represent the potential outcomes, the probabilities of all the branches leaving a chance node add to 1.

Decision nodes are followed by chance nodes. Multiple chance nodes can be connected in order to better describe the evolution of uncertainty. The architecture of a decision tree is illustrated in Figure 3-4.

It can be seen clearly that both flexibility and uncertainty are made apparent in the decision tree. Decision nodes represent the managerial flexibility embedded in the system whereas chance nodes represent the evolution of the underlying uncertainty. The information gained at chance nodes prior to a decision node can be used by managers to make a better choice. The decision tree represents all possible scenarios. A scenario is a path in the decision tree meaning a succession of decisions and events that describes the resolution of uncertainty and the corresponding reaction of managers.

Valuation process The principle of Decision Tree Analysis is to consider and compare all possible scenarios to derive what is the best strategy to follow. Managers are assumed to maximize the expected value of the project over the time horizon considered. At each decision node, the optimal decision is therefore the one that maximizes the expected value of the project over the rest of the time horizon. The most efficient way to determine this optimal path is to adopt a backward process working from the end of the tree back to the first node.

The first step is to calculate the value obtained for each possible scenario. This value is written at the corresponding end point of the tree. The calculation then proceeds step by step towards the left of the tree. The calculation is different depending on the type of node encountered:

- **At chance nodes:** At a chance node, different events may occur, each characterized by a probability of occurrence and the value obtained if this event occurs, calculated at the previous step. The expected value of all branches at each chance node is computed and written on top of the chance node as illustrated in Figure 3-5.
- **At decision nodes:** At a decision node, the value obtained for each decision is known from previous calculations. The optimal decision is determined that maximizes the value of the project as illustrated in Figure 3-6. This decision is the one that the

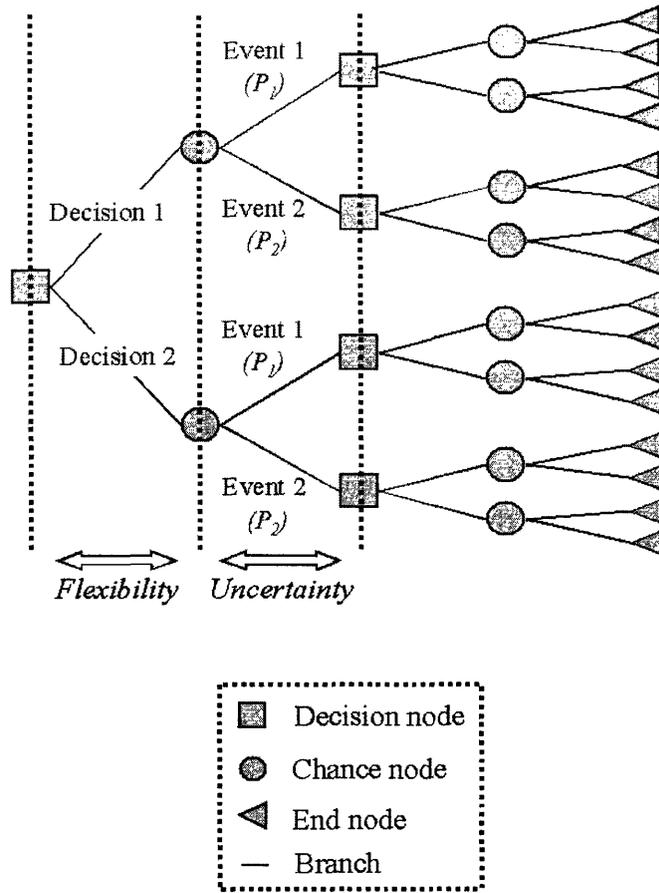
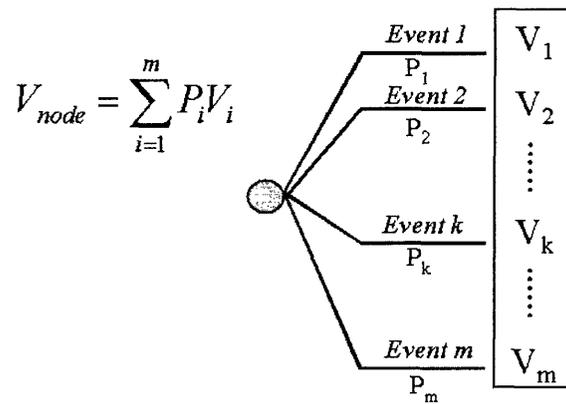


Figure 3-4: Illustration of a decision tree.



All branches are kept

Figure 3-5: Calculation at a chance node.

managers should choose, the other are cut from the tree as they are not optimal.

This process is carried out back to the first node of the tree. The value obtained at the initial node is the expected value of the project. The flexibility value can then be deduced by comparing this expected value with the expected value of a fixed system. The computation through the tree also provides the optimal strategy that managers should follow to maximize value. This strategy is represented by the decision branches still apparent in the tree. It must be noted that a strategy is not a single path in the tree: managers have an impact on decision nodes but not on chance nodes and all possible events are still present in the tree. The end result obtained after a complete analysis of a decision tree is shown in Figure 3-7. This result has been obtained using a Decision Tree Analysis software (DATA 3.5). The branches crossed correspond to the decisions cut off the tree. The value at each node is shown on the node itself.

Advantages of Decision Tree Analysis The Decision Tree Analysis method offers an easy way to represent the origin of the value of flexibility and the concept of a dynamic strategy that evolves as uncertainty is resolved. The Decision Tree illustrates nicely the interaction between uncertainty and the decisions to be taken. The concept of the DTA method is easy to grasp since it determines a map of the future outcomes. The value at each node in the decision tree may be represented by the Net Present Value of the expected cash

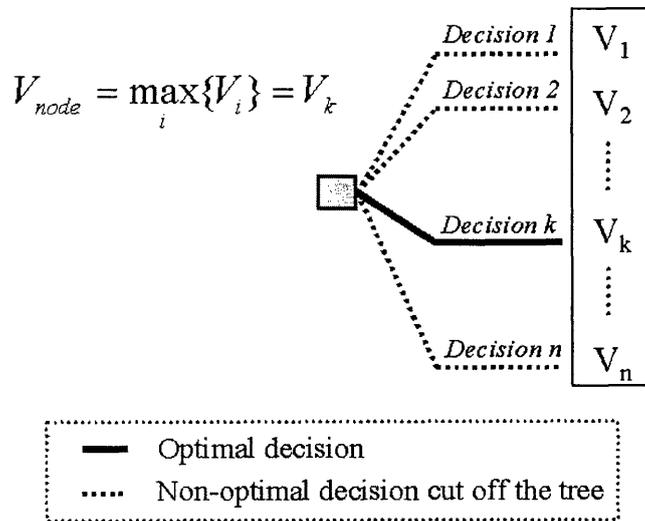


Figure 3-6: Calculation at a decision node.

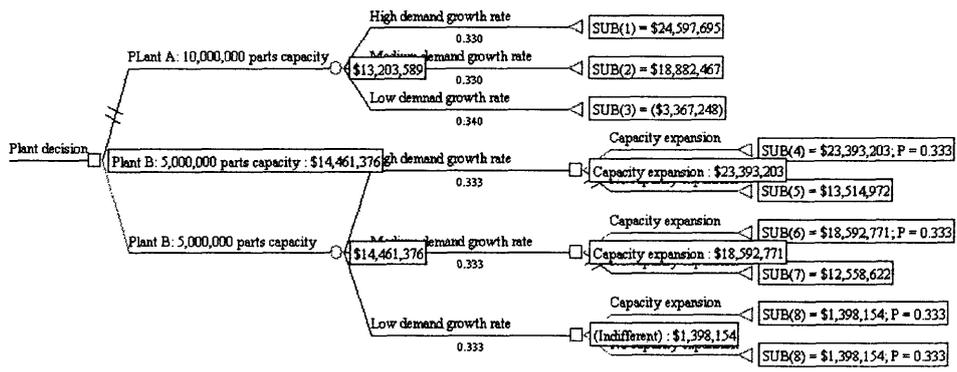


Figure 3-7: Solution obtained using a Decision Tree Analysis software (DATA 3.5).

flows. However, the main difference with the Net Present Value method is that Decision Tree Analysis does not consider a fixed sequence of decisions but consider a dynamic sequence of decisions that varies depending on the evolution of uncertainty. Decision Tree Analysis can also easily be adapted to non monetary values by using a utility metric as the objective to maximize.

Limitations of Decision Tree Analysis Representing all possible scenarios in a decision tree is a nice process to understand the system and the impact of uncertainty. However, the complexity of the tree grows rapidly with the number of decisions and uncertainty events considered. The decision tree can rapidly become a “decision bush”, difficult to capture and computationally expensive to solve. This in turn makes it difficult to realistically model continuous sources of uncertainty since the number of events must be limited to keep the tree to a reasonable size.

If value is represented by the discounted cash flows generated by a project, Decision Tree Analysis is sensitive to the choice of the discount rate as is the Net Present Value method. It must finally be noted that the results obtained by Decision Tree Analysis does not represent any real value the project will take but only an expected value. The simple example of a coin tossing game can illustrate this idea. Let’s consider the following game: the coin is tossed once, heads corresponding to a gain of \$10, and tail to a loss of \$5. There is a 50% chance of getting head or tail. Therefore the expected value EV of this game is:

$$EV = 0.5 \times 10 + 0.5 \times (-5) = \$2.5 \quad (3.3)$$

However, the player will never receive \$2.5 if the coin is tossed only once: it will either gain \$10 or lose \$5. The expected value would represent what the player could receive only if the game was to be played many times. This must be taken into account when considering the expected value given by a Decision Tree Analysis.

Real Options Analysis

Real Options Analysis adopts a completely different approach based on the pricing of financial options.

Financial options There are two main types of financial options: call options and put options. A call option is a contract that gives the holder the right but not the obligation to buy a certain amount of stocks at a certain price in a certain time frame. A put option is similar to a call option but refers to a contract that gives the right to sell rather than buy a certain amount of stocks. The price set on the contract is the exercise price. The option is said to be exercised if the holder decides to use the option to buy (respectively) sell stocks. The time at which the option expires is called maturity or expiration date. Options can be classified in two categories depending on the time constraint imposed: American options can be exercised at any time before the maturity date whereas European options can only be exercised at the maturity date. Options have a price and are traded on financial markets. We will refer to the initial cost of buying an option as the option price.

Options are very particular assets that offer asymmetric payoffs. Payoffs refer to the profit made if the option is exercised immediately. This can be best illustrated by using a simple example. Let's consider a stock whose current price is \$100 and a European call option on this stock with an exercise price of \$110. The price of the option is assumed to be \$10. The holder of the option has the right but not the obligation to buy one stock at a price of \$110. If the price of the stock on the financial market is below \$110, the holder will not exercise the option since he can buy a stock in the market for a lower price than the exercise price. The payoff of the option is therefore \$0 since the option is not exercised. If the price of the stock goes above \$110, the holder can exercise the option. The payoff will be the difference between the market price of the stock and the exercise price. If S represents the market price of the stock, the payoff of the option is: $\max(S - \$110, 0)$. Figure 3-8 shows both the option payoff and the profits when taking into account an option price of \$10. The call option offers an asymmetric return with limited losses and potential high profits. The maximum loss is limited to the price of buying the option (in the example the maximum loss is \$10). On the contrary, significant profits can be made if the price of the stock increases far above the exercise price. Put options also have asymmetric payoffs and profits, but in this case the holder is betting on a decrease in the price of the stock. It must be noted that option payoffs and option value are two different concepts. The payoffs refer to the profit realized if the option is exercised immediately. The value of an option corresponds to the price somebody would be willing to pay to get this option. It may differ from the immediate payoffs because the value also includes the expectations of future profits if the

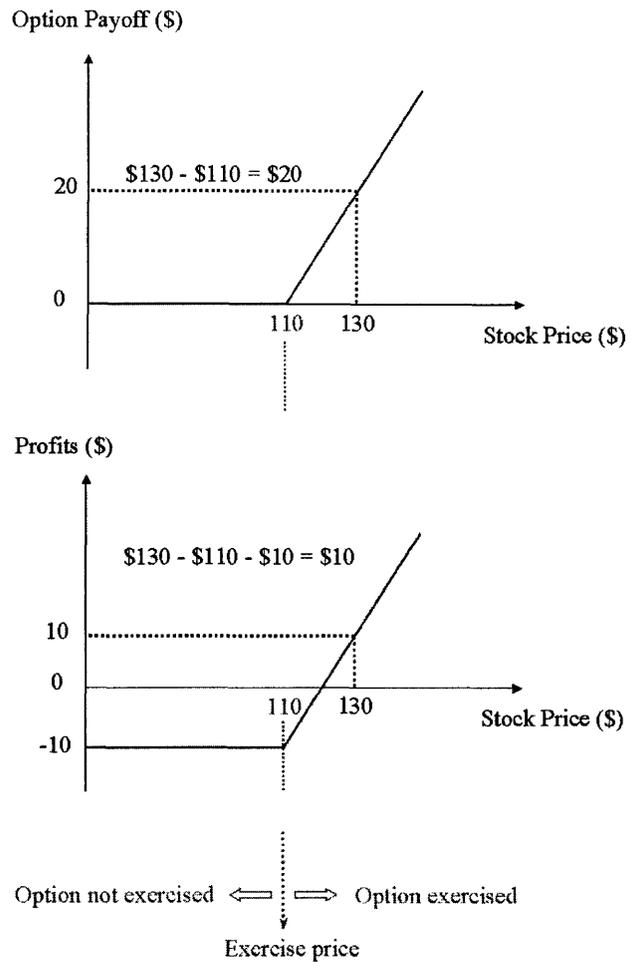


Figure 3-8: Asymmetric payoffs and profits for a European call option.

Call-like Real Options	Put-like Real Options
Option to wait Wait to launch a new space mission	Option to abandon Abandon a space mission
Option to Expand Upgrade, incorporate new technologies, increase capacity of space mission	Option to contract Not often used in space systems since operational costs are small compared to IOC costs
Option to restart operations Restart satellite operations	Option to shut down operations Temporarily stop satellite operations

Table 3.3: Examples of real options.

option is not exercised immediately. For example, if the stock price is equal to the exercise price, payoffs are equal to \$0. However, the stock price has a probability to increase in the future. If the option was to be kept and not exercised, it could be exercised later if the stock price increased above the exercise price. Therefore, the value of the option is positive whereas the payoffs are null.

The value of an option depends on various parameters. In particular, the value of an option increases with the degree of variation in the stock price, called the volatility of the stock. A higher volatility means that there is a higher uncertainty about the price of the stock that may be very low or very high. Since an option offers asymmetric returns, acting as an insurance that limits the potential losses if the stock price decreases while still offering profits if the stock price increases, a higher uncertainty only translates to potentially higher profits therefore increasing the value of the option.

Real options Options on real assets present similar characteristics to options on financial assets discussed in the previous paragraph: they offer the option but not the obligation to acquire or modify a project or a real asset at a certain price in a certain time frame. In analogy to financial options, real options can be classified as call-like options and put-like options. Table 3.3 gives some examples of real call and put options. Two types of real options can be distinguished: real options on systems and real options in systems. Real options that consider the system as a whole are called real options on systems. Real options that apply to the inside of a system or a project are called real options in systems. Choosing to adopt a modular design or installing a docking system on board a satellite in order to have the opportunity to conduct an upgrade operation is a real option in systems.

An analogy between the characteristics of financial options and real options can be drawn.

Financial Options	Real Options
Underlying Stock	Equivalent traded asset or Present value of real asset
Maturity date	Time limit to use the option
Option price	Investment necessary to acquire the option ex: cost of designing a satellite for serviceability
Exercise price	Price to use the option (ex: cost of a servicing operation)

Table 3.4: Analogy between financial options and real options.

Embedding flexibility in systems has a cost which can be compared with the price of buying the option or option price. Using the option may have a cost, such as the cost of the servicing mission if the decision to upgrade the satellite is chosen, that is comparable to an exercise price for a financial option. Moreover, the opportunity to use real options may be limited in time for example by the lifetime of the project. Real options may also have a maturity date. Finally, the payoffs and the value of a financial option depends on the price of the underlying stock. In the case of real options, there may be a corresponding asset traded on financial markets that represents the project and can be used as the equivalent of stocks for financial options. However, it is often hard to find a traded asset that characterizes the project of interest and it is current practice to consider the expected present value of the project or real asset as the basis for the evaluation of real options. The analogy between financial and real options is summarized in Table 3.4. This close analogy between real options and financial options lead economists to apply financial option pricing theory to the valuation of real assets and projects.

Valuing financial options Option pricing relies on the concept of arbitrage pricing. In a perfect market there should not be any arbitrage opportunity. This means that if two investment opportunities have the exact same payoffs in all possible outcomes and the same level of risk, they should have the same price. If a price discrepancy existed, one could buy the cheapest portfolio and sell the most expensive one. The payoffs being the same, the price difference would be a risk free profit. As demand for the cheapest portfolio increases, its price will also increase whereas, as the more expensive portfolio is offered on the market, its price will decrease. Finally at equilibrium the two portfolios will have equal price.

This principle can be used to evaluate the price of a portfolio or a financial asset. A

portfolio is constructed that replicates exactly the outcomes of the asset to be priced and that is subject to the same level of uncertainty. It is referred to as the replicating portfolio. Since no arbitrage opportunity is available, this replicating portfolio has the same price as the asset of interest. Arbitrage pricing is based on the construction of a replicating portfolio that can be priced more easily.

When pricing options on a stock, the replicating portfolio is chosen as a combination of N shares of the underlying stock and a amount B of borrowed money such as to replicate the payoffs of the option. Let's consider a simple example to illustrate the construction of the replicating portfolio for a financial option. The aim is to price a European call option on a stock. The current price of the stock S is \$100. The future price of the stock at the option maturity date is uncertain: the stock price can go up to $S^+ = \$150$ with a probability p or down to $S^- = \$70$ with a probability $1-p$. The exercise price of the call option is \$110. The evolution of the stock price and the resulting payoffs of the call option are shown in Figure 3-9: C represents the current price of the option, C^+ the payoff if the stock price increases and C^- the option payoff if the stock price decreases. The replicating portfolio is composed of N shares of the underlying stock and an amount B of borrowed money at the risk free interest rate $r = 10\%$. The price and payoffs of the replicating portfolio are summarized in Figure 3-10. By construction, the payoffs of the replicating portfolio are equal to the payoffs of the call option.

$$\begin{cases} -B(1+r) + NS^+ = C^+ \\ -B(1+r) + NS^- = C^- \end{cases} \quad (3.4)$$

N and B are calculated from the set of equations 3.4

$$\begin{cases} -1.1B + 150N = 40 \\ -1.1B + 70N = 0 \end{cases} \quad (3.5)$$

$$\Leftrightarrow \begin{cases} N = \frac{1}{2} \\ B = \frac{70}{2 \times 1.1} \simeq 31.82 \end{cases} \quad (3.6)$$

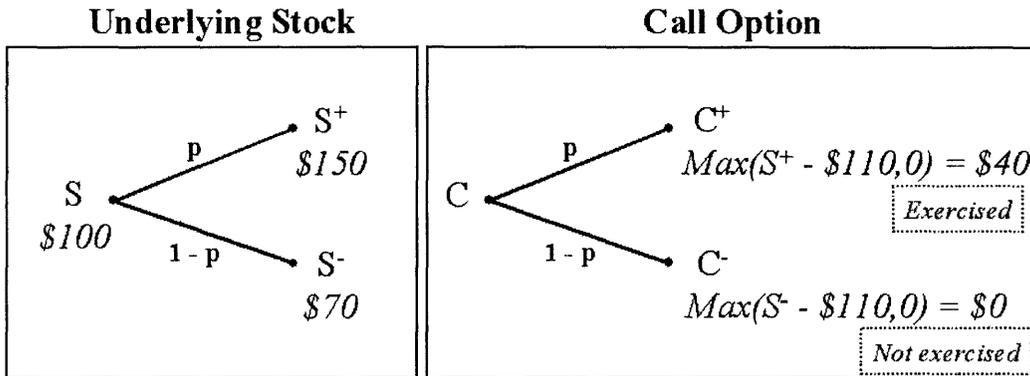


Figure 3-9: Evolution of the underlying stock price and the call option price and payoffs.

From the principle of arbitrage pricing, the current price C of the call option must be equal to the current price of the replicating portfolio given by the following equation:

$$C = NS - B \tag{3.7}$$

In our example this leads to the following option price:

$$C = \frac{1}{2} \times 100 - \frac{70}{2 \times 1.1} \tag{3.8}$$

$$\simeq \$18.2. \tag{3.9}$$

It can be noted that the probability of the different outcomes are not used to determine the price of the option in this process. Moreover, only the risk free rate is involved in the calculation.

A short cut technique called risk neutral valuation is often used to calculate the option value. A parameter q , referred to as the risk neutral probability, is used to calculate the expected value discounted at the risk free rate. The value found with the replicating portfolio technique is equal to the expected value calculated as if there was a probability q of getting the highest estimate and a probability $1 - q$ of getting the lowest estimate:

$$C = \frac{qC^+ + (1 - q)C^-}{1 + r} \tag{3.10}$$

It must be noted that q is not a real probability but an intermediary coefficient used to simplify the calculation. It is often called risk neutral probability because of the role q plays

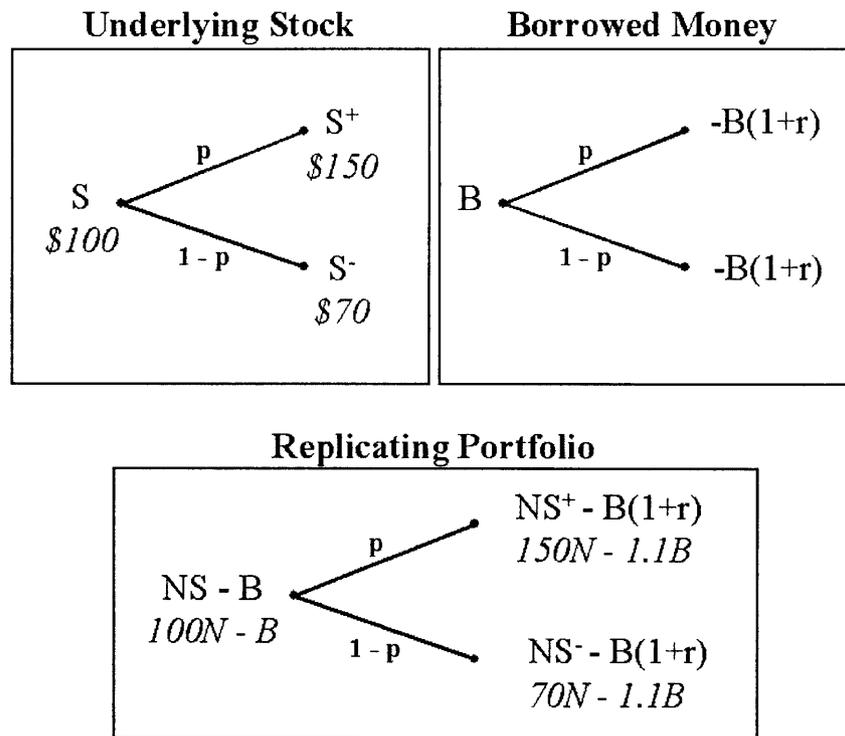


Figure 3-10: Replicating portfolio price and payoffs.

in Equation 3.10, which is similar to a real probability. The use of q allows the cash flows to be discounted at the risk free rate.

Valuing real options By analogy with financial option pricing, two methods have been proposed to price real options [11]: contingent claim analysis and dynamic programming. Contingent claim analysis is analogous to the option pricing method described for financial options. The price of the real option is deduced from the construction of a replicating portfolio. The issue is in determining what is the equivalent of the underlying stock for real options. If the real asset is traded, the market price of the asset is chosen as the equivalent of the stock price. If the asset is not traded, it is assumed that the market is rich enough to find a portfolio of traded assets that will have the same uncertainty characteristics as the real asset. Only the uncertainty of the asset has to be reproduced. This portfolio combined with borrowed money is taken as the building blocks for the replicating portfolio. More than one period can be considered to better represent the evolution of uncertainty. The replicating portfolio is modified at each period to conduct the valuation.

However, in practice, it may be quite difficult to find a portfolio that exactly reproduces the uncertainty of the real asset to be priced. Dynamic programming has been developed to avoid this issue. The concept of Dynamic Programming is close to Decision Tree Analysis and also adopts a backward process. The main concept behind dynamic programming is described by Pindyck in the following quote [11]:

“It breaks a whole sequence of decisions into just two components: the immediate decision, and a valuation function that encapsulates the consequences of all subsequent decisions, starting with the position that results from the immediate decision.”

An optimal strategy is derived as with DTA. The risk neutral valuation method can be used to estimate the value at each period. The mechanics of dynamic programming will be described in more details in Chapter 4 when considering the case of commercial space missions.

Advantages of Real Option Analysis As DTA, Real Option Analysis considers an optimal dynamic strategy, the sequence of decisions depending on the evolution of uncertainty. Therefore, Real Option Analysis manages to capture the value of flexibility. Moreover, Real Option Analysis is the only method to solve the problem of choosing an adequate discount rate since only the risk free discount rate is needed for the valuation. The risk free discount rate is easier to determine since it is independent from the level of risk specific to the project. On the contrary of DTA, the real options method does not consider an expected value: real probabilities are not used in the calculation. The value of the option is determined through the current prices of traded assets that reflect the expectations of future returns. Finally, this method can more easily handle continuous uncertainty probability distributions and continuous decision making.

Limitations of Real Option Analysis However, it must be recognized that this valuation method is not always easy to implement. First the process is not as easy to explain as the DTA since it relies on financial concepts. Managers may find it easier to understand the process of solving a decision tree than the construction of a replicating portfolio. Moreover, the valuation is sensitive to the uncertainty model adopted. Modelling the volatility and the evolution of uncertainty in real projects is often a delicate process. The models chosen

to characterize the evolution of the price of financial assets are often not adapted to real assets not traded on the market. In addition, real projects often have specific constraints and characteristics that drive their value but are too complex to incorporate in the model. Finally, since the method is derived from financial concepts, it is not well suited to deal with non monetary utilities that may prevail in real projects.

3.4 New proposed framework for evaluating on-orbit servicing

Based on the limitations of traditional valuation methods identified in Section 3.1.2, Lamassoure and Saleh [33] proposed a different framework for the evaluation of on-orbit servicing. This framework aims at providing general insights on the intrinsic value of on-orbit servicing by adopting a customer oriented point of view. In order to take into account the added value of flexibility, the valuation process relies on Decision Tree Analysis and Real Options Analysis. The main principles motivating the choice of this framework as the preferred valuation process are first summarized before describing the method in more details. Finally past studies that aimed at capturing the value of the flexibility offered by on-orbit servicing are presented.

3.4.1 Framework principles

The framework used in this study is based on two main principles [32]: first a customer's perspective is adopted to study the value of on-orbit servicing and second, the value of flexibility is taken into account in the valuation process.

Adopting a customer's perspective

Previous valuations studied on-orbit servicing from the point of view of a provider looking at specific servicing architectures and their cost to be amortized over some mission. However, as discussed in Section 3.1.2, the cost of servicing is highly uncertain and depends largely on the specific servicing architecture chosen and on strategic/political choices. No general conclusions could be derived about the intrinsic value of on-orbit servicing for space missions. The new framework proposes to conduct the study from a different perspective by looking separately at the value and the cost of on-orbit servicing. The value of on-orbit

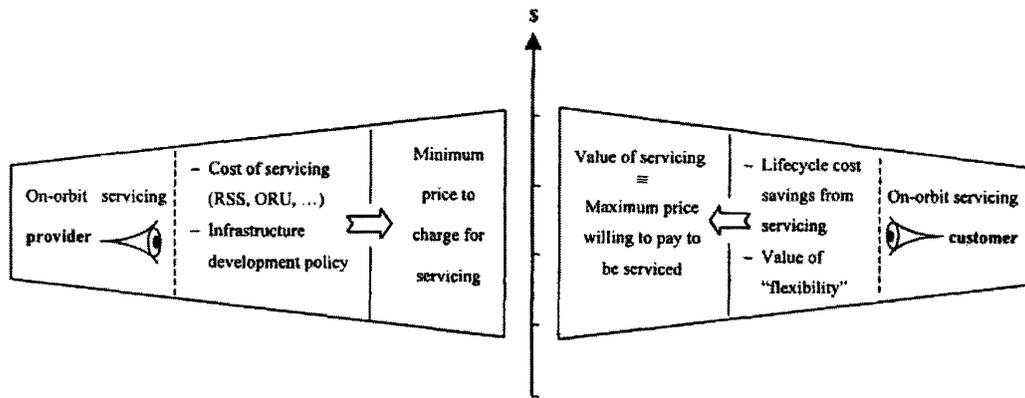


Figure 3-11: Two perspectives for the study of on-orbit servicing: customer's perspective and provider's perspective [32].

servicing is defined as the maximum price a potential customer would be willing to pay to get a satellite serviced. This new approach corresponds to switching from a provider's perspective to a customer's perspective. The price of servicing is a parameter in the model set independently from any servicing architecture design or cost. Therefore, the uncertainty in cost, the difference between price and cost of servicing and the dependence on a specific servicing architecture do no impact the results. In turn, the value of servicing can be used as an input to the design of the servicing infrastructure. Looking at the maximum price a customer would be willing to pay is similar to an economic study of the demand for the market of servicing. It can be very useful for potential providers to determine where are the largest opportunities for servicing, what are the most promising servicing architecture candidates and what are the conditions for a profitable servicing business. Figure 3-11 illustrates the two different approaches to the study of on-orbit servicing [32].

Capturing the value of flexibility

When estimating the maximum price a customer would be willing to pay for a servicing mission, both potential cost savings and the value offered by the additional flexibility should be taken into account. It has been argued that a significant characteristic of on-orbit servicing is to offer managers an increased degree of flexibility and options to react to uncertainty. To capture the potentially significant value of this flexibility, Decision Tree Analysis and Real Options Analysis are preferred over traditional valuation processes such as the Net Present Value method.

3.4.2 Framework building blocks and valuation process

The detailed valuation process has to be tailored to the type of mission studied - commercial, military or scientific - since the utility metric and the uncertainty source may greatly differ. Some common building blocks can however be identified that characterize any valuation process. The major components used in the valuation process are presented in this section. For a more detailed description of the framework the reader is referred to Lamassoure [16].

Uncertainty description Flexibility has no value in a world of certainty. Therefore, one assumption is that the value of the mission depends to some degree on at least one uncertainty parameter X . The different sources of uncertainty that will be incorporated in the model must be defined and their evolution must be characterized. Examples of uncertain parameters can be market demand, technology state of the art or the location of a war for a military space mission. Uncertainty parameters are modelled as stochastic processes and are noted X .

The uncertainty is assumed to be external to the mission which means that decision makers have no impact on uncertainty. The evolution of the uncertainty parameter does not depend on the decisions made during the mission lifetime. The flexibility embedded in the system is not used to reduce uncertainty but allows the system to be adapted to react to changes. Moreover, it is assumed that each uncertainty parameter follows a Markov process. Therefore the distribution of the uncertainty parameter at a time $t > t_0$ only depends on the value of the uncertainty parameter at time t_0 and not on the path followed prior to t_0 . The assumption of a Markov process is often made to characterize the evolution of stock prices on the basis that public information about the past is reflected in the stock price. Based on a similar argument, Markov processes can be considered valid for most sources of uncertainty linked to the market. It can also be considered that the occurrence of a random event, such as the random failure of a component, is not related to past history and therefore can be described by a Markov process.

Time horizon of the study A common time horizon must be chosen to compare the different alternatives over the same time frame. The period over which the valuation is carried out has to be chosen so that it captures the period of interest for decision makers

and corresponds to a significant time period for the resolution of the underlying uncertainty. For example, a possible time horizon for the upgrade of a mission is the lifetime of the initial satellite. The time horizon is noted T_H .

Decisions Flexibility offers decision makers with options to alter the system during its lifetime. The decision process is characterized by:

- **Time of the decisions: Decision points** The points in time at which managers have the opportunity to take a decision are called decision points. A discrete set of decision points are considered in the model: $0 = T_0 < T_1 < \dots < T_{N-1} < T_N = T_H$, T_0 being the initial time at which the satellite is launched and T_H the end of the time horizon for the study. The uncertainty parameter observed at time T_k is noted $X(T_k) = X_k$.
- **Potential decisions available** Depending on the degree of flexibility, the different alternatives offered to managers are derived, which represent the possible decisions to be made D_i for $i \in [1, d]$ at each decision point. The decision to abandon the mission, to upgrade, to service or to replace a satellite mission can be some examples of decisions made available to managers.
- **State of the system and mode of operations** The state of the system resulting from the decisions made is referred to as the mode of operation of the system and represented by superscript letters. A decision to alter the system corresponds to a switch from a mode of operation (n) to a mode of operation (m) and will be noted as $(n \mapsto m)$. The state of the system n before the decision has been taken is referred to as the entry state of the system. The state of the system m after the decision has been taken is referred to as the end state of the system. As an example, mode of operations can correspond to the technology embedded in the satellite. Upgrading a satellite to incorporate a new technology would correspond to a switch from mode of operation (n), representing the former technology, to mode of operation (m), representing the new technology.

Utility metric Utility represents a measure of the benefits to the decision makers. For a commercial mission, utility is often taken as the discounted revenues expressed in monetary

unit. For military or scientific space missions, utility may be a non monetary value. A possible measure of utility for a space telescope for example can be the amount of data generated, the number of discoveries or the number of publications based on the space telescope data. The utility often depends on the uncertainty parameter and therefore is a stochastic process as well.

Matrix of switching costs Costs must be evaluated as well as benefits. The discounted costs are calculated at each period and take into account the cost of operation of the space system and the cost associated with the decisions made. In the initial period, the costs to initial operating capability (IOC), combining the cost of designing, producing and launching the initial satellite, must be added. The costs associated with the decisions taken can be summarized in a matrix called the matrix of switching costs. The rows and columns of the matrix represent the different possible modes of operations of the system. The entry at row i and column j represents the cost to switch from mode of operation i to mode of operation j noted $C^{(i \rightarrow j)}$.

Value metric The value metric represents the trade off managers make between utility and cost. For commercial missions, value is often taken as the difference between revenues and costs. When utility is a non monetary value, the value metric may be harder to define. It is sometimes taken as a utility per cost measure $\frac{U}{C}$. Value is also a function of the uncertainty parameter and is a stochastic process.

Decision model In order to model the decision process, a decision rule must be defined. This decision model captures the rationale followed by decision makers when deciding on the mode of operation of the system. The decision model is often to maximize the value metric. In some cases, a decision is taken only if the value metric exceeds a predefined threshold. At each decision point, the value metric is computed for each possible decision and the optimal decision is determined based on the decision model.

Flexibility value The value of flexibility FV is determined by comparing the value of a flexible mission V_F with the value of a baseline non-flexible system V_B (Equation 3.11). The value of flexibility will often be normalized to the baseline value (Equation 3.12). It must be noted that the valuation process may focus on capturing the value of a set of options

but other options may be embedded in the system. A baseline must be defined to clearly distinguish between the baseline options and the additional options that are investigated and valued. For example, in the study of the value of on-orbit satellite upgrade, the option to abandon the mission may be considered as a baseline option always made available to the decision maker whereas the option to service and upgrade the satellite are available only for the flexible system. There can be many sources of flexibility and the specific degree of flexibility considered in the valuation process must be determined through the definition of a baseline non flexible system.

$$FV = V_F - V_B \quad (3.11)$$

$$\frac{FV}{V_B} = \frac{V_F - V_B}{V_B} \quad (3.12)$$

Analysis and conclusion Different conclusions can be derived from the model:

- **For a given servicing price** If a certain value of the servicing price is used as an input to the model, the expected value of the flexible mission corresponds to the maximum cost penalty a space operator is willing to pay to design the satellite to be serviceable (if no cost penalty is already incorporated into the model). Moreover, the expected number of servicing operations gives the potential demand for servicing at this servicing price. Therefore, a demand curve, illustrating the level of servicing demand as a function of servicing price, can be derived for the servicing market.
- **By varying the servicing price** If the servicing price is considered as a varying parameter in the model, the servicing price at which the flexibility value drops to zero corresponds to the maximum price a customer is willing to pay for a servicing mission: this price is the price at which the value of a flexible mission equals the value of the non-flexible mission and servicing will not be chosen as the preferred solution.
- **On-orbit servicing as the preferred alternative** Different architectures can be computed and compared to determine what are the conditions for which on-orbit servicing is the preferred alternative.
- **Flexibility value** Finally, the importance of the flexibility value in the total value of the mission gives insights on how much previous studies underestimated the value of on-orbit servicing.

It must be noted that all alternatives available to space operators must be carefully studied to capture the real value of on-orbit servicing. As an example, let's consider the case of the upgrade of solar cells using on-orbit servicing. The alternatives to servicing are to keep the original satellite or to replace the original satellite by launching a new satellite. However, the type of solar cells used also has an impact on the value of on-orbit servicing and must be incorporated as a parameter in the study.

3.4.3 Previous on-orbit servicing valuations taking into account the value of flexibility

The idea of taking a different approach to valuing on-orbit servicing in order to take into account the value of flexibility has been applied to the study of the optimal lifetime of a satellite, the use of refueling for both commercial and military missions and the specific case of the refueling of GEO communication missions. Both the customer's and the provider's point of view have been explored.

Case of refueling servicing missions

Lamassoure [16] studied the refueling of satellites in orbit for the case of a commercial mission facing uncertain revenues and for the case of a thin military radar constellation with a dynamic distribution of contingencies. The study concluded that on-orbit servicing seemed promising for some conditions and that the value of flexibility, previously not taken into account, can correspond to a large part of the total value of the mission.

The maximum servicing price for a commercial space mission was in some cases estimated to be an order of magnitude higher than the cost of developing and launching the required servicing mass for market volatilities above 40%/year.

In the military case studied, a Markov model is used to model the uncertainty in the location of the contingencies. Different propulsion types are compared to analyze the value of satellite refueling to manoeuvre and reconfigure the constellation in order to optimize the coverage over contingencies. On-orbit refueling does not appear to offer a large value for LEO constellations whereas it seems promising for GEO constellations.

Optimal lifetime of a satellite

Saleh [32] applied the new framework to capture the value of the lifetime extension option offered by on-orbit servicing. Two decision models were studied: minimizing cost in the case of a non-profit organization and maximizing profit in the case of a for-profit organization. The conclusions emphasize the importance of accounting for the added flexibility in the valuation of on-orbit servicing.

Commercial Geostationary communication satellites

The potential for a servicing market for GEO communication satellites has been investigated by Mc Vey [22]. Different strategies are compared that use space tugging or on-orbit refueling. One particularity of this work is that the analysis has been done both from the perspective of the provider and the customer to derive conclusions about the potential development of a viable servicing infrastructure. The study recommends the use of on-orbit servicing for refueling GEO communication satellites every year. It must be noted however, that the risk of a servicing failure has not been included in the model.

Orbital transportation network for on-orbit servicing

Nilchiani [27] adopted an original point of view in analyzing the design of an on-orbit servicing infrastructure for refueling by analyzing the potential value of embedding flexibility in the design of the servicing infrastructure as compared to the flexibility offered to the customer. The servicing infrastructure is modelled as an orbital transportation network using System Dynamics. The performance of an architecture is defined as the product of an availability metric, defined as the ratio of completed missions to demanded missions, and a reliability metric, defined as the fraction of successful missions. Servicing architectures are proposed which are robust against market demand variations.

Chapter 4

Towards evaluating the upgrade of commercial missions

The definition of the utility, the value and the decision model characterizing the mission is specific to each type of space mission. The general framework described in Section 3.4 must be applied to the case studied. In this chapter, we will focus on the case of a commercial mission facing an uncertain market and define the model used for the evaluation. Two main characteristics distinguish commercial space missions. First, the decision makers are assumed to follow a future profit maximizing goal. Second, utility and cost can be expressed as monetary values and alternatives can be easily compared through the calculation of profits. Building on those two characteristics, the implementation of the valuation method is derived using Real Options Analysis and dynamic programming.

4.1 Definition of the problem and notations

Commercial space missions are closer to financial valuations since they consider monetary utility and value functions and aim at maximizing future profits as investors do in financial markets. Therefore, financial methods can be applied more directly simplifying the valuation process. This section describes the different assumptions and notations that are used for commercial mission examples.

4.1.1 Uncertainty

Uncertainty parameter definition

The value of a commercial mission is highly dependent on the dynamics of the market the satellite is serving. This uncertainty can be represented as uncertain revenues for the mission considered or as uncertain levels of demand for the satellite services. In the commercial world, market forecasts are often done to predict the evolution of market demand. The actual level of demand or revenues however is uncertain and fluctuates above or below this forecast.

The uncertainty in actual revenues/demand is modelled in reference to the forecast level. The uncertainty parameter used in the model is defined as the ratio of actual revenues/demand \mathcal{B}_{Act} to forecasted revenues/demand \mathcal{B}_F :

$$X = \frac{\text{Actual revenues/demand}}{\text{Forecasted revenues/demand}} = \frac{\mathcal{B}_{Act}}{\mathcal{B}_F} \quad (4.1)$$

Uncertainty distribution: Geometric Brownian Motion

The distribution chosen to describe the evolution of revenues/demand is a Geometric Brownian Motion with drift α and volatility σ , which is often used in real options theory to characterize the evolution of stock prices:

$$dX = \alpha X dt + \sigma X dz \quad (4.2)$$

where dz represents the increment of a Wiener process, α and σ are constants.

A Wiener process is a continuous stochastic process that has three main properties: 1) It is a Markov process, which means that the distribution for future values only depends on the current value; 2) The increments of a Wiener process are independent: the probability distribution for the change in the process over any time interval is independent of any other non overlapping time interval; 3) Changes in the process over any finite time interval are normally distributed with a variance increasing linearly with time [11]. For more details on the theory of Wiener processes the reader is referred to Trigeorgis [35] or Pindyck [11].

A Brownian Motion with drift is a generalization of a Wiener process to more complex

processes taking into account a drift with time:

$$dy = a(y, t)dt + b(y, t)dz \quad (4.3)$$

where dz is an increment of a Wiener process and a and b are functions of y and t .

The Brownian Motion can be understood as the continuous limit of a discrete-time random walk. This analogy will be explained in more details in Section 4.3 when a numerical analysis of the problem is described but the concept is first presented here to get insights on the meaning of the assumption of a Brownian Motion distribution. Let's consider discrete time intervals Δt and the special case where a and b are constants. During each time interval y can go up or down by an amount ΔH_y with the respective probability p and $1 - p$. The potential values of y can be represented in a tree as illustrated in Figure 4-1. The evolution of y corresponds to a random walk in this resulting tree as shown by the solid path in Figure 4-1. ΔH_y and p are set so as to reproduce the expected drift and volatility of the Brownian Motion distribution. It must be noted that the process is a Markov process since the distribution of future values of y only depends on the current value of y in the tree. The increments of y are independent and the probability of y going up or down is independent of the prior path of y . The continuous Brownian Motion is the limit of this discrete process as $\Delta t \rightarrow 0$. Graphs a and b in Figure 4-2 illustrate the Brownian Motion distribution for both 40 time steps and 2000 time steps [7]. The expected value and the $\pm 40\%$ intervals are also shown.

The Geometric Brownian Motion proposed in this study is a special case of a Brownian motion for which the functions a and b adopt a specific form:

$$\begin{cases} a(y, t) = \alpha y \\ b(y, t) = \sigma y \end{cases} \quad (4.4)$$

with α and σ constant parameters.

A better understanding of the distribution and the meaning of the parameters α and σ can be obtained by looking at the discrete-time model of a Geometric Brownian Motion:

$$\frac{\Delta X}{X} = \alpha \Delta t + \sigma \epsilon \sqrt{\Delta t} \quad (4.5)$$

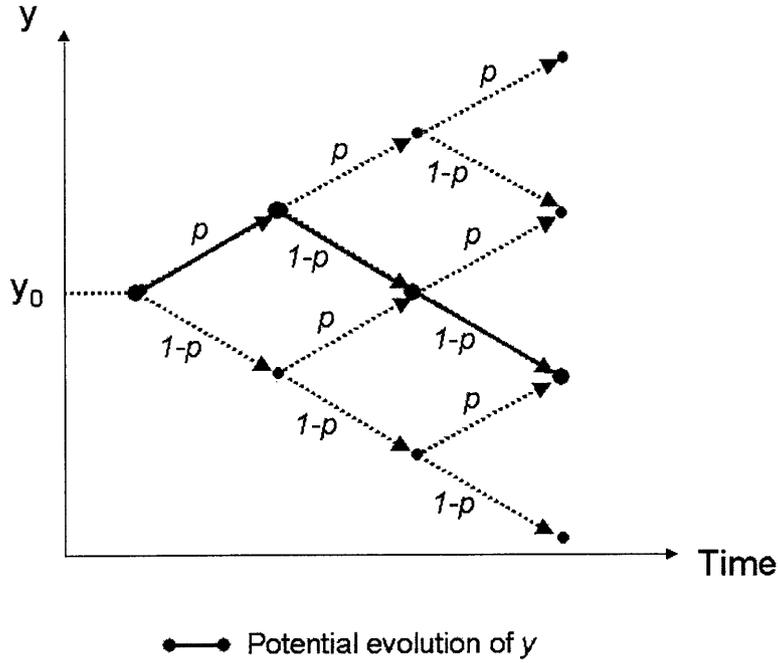


Figure 4-1: Random walk representation of a Brownian Motion.

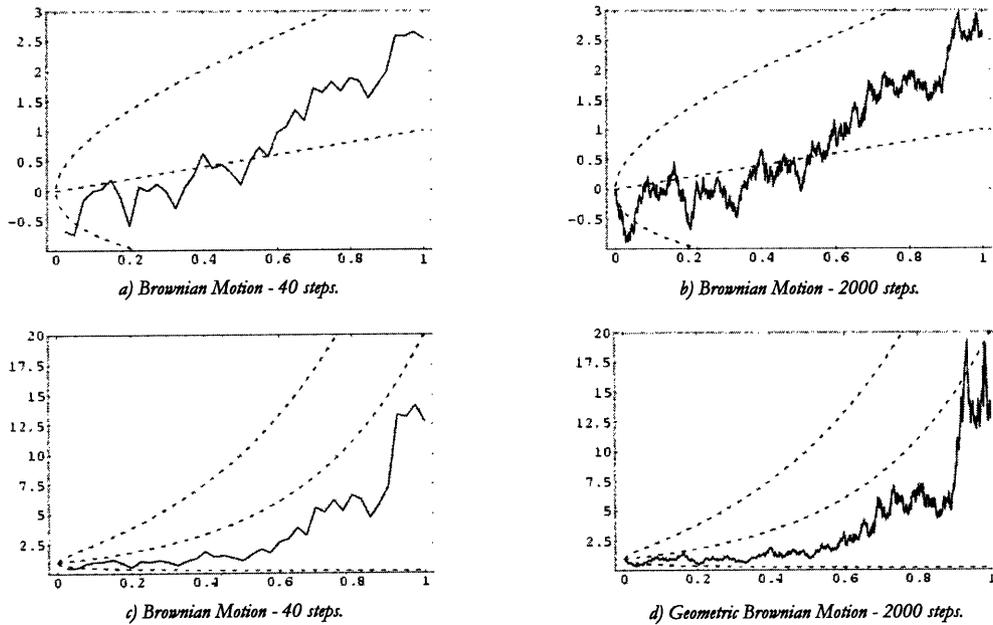


Figure 4-2: Brownian and Geometric Brownian Motion paths. The expected value and the $\pm 40\%$ intervals are also shown. Samples of 2000 and 40 points are generated to show the convergence from discrete to continuous time [7].

where ϵ is a random variable following a standard normal distribution, Δt is the time step of the discrete-time model and ΔX represents the variation in X . $\frac{\Delta X}{X}$ represents the rate of variation of X over the time interval Δt .

- **Drift α** Let's consider the expected value of the rate of variation of X in the discrete-time model:

$$E\left[\frac{\Delta X}{X}\right] = E[\alpha\Delta t] + E[\sigma\epsilon\sqrt{\Delta t}] \quad (4.6)$$

$$= \alpha\Delta t + \sigma\sqrt{\Delta t}E[\epsilon] \quad (4.7)$$

where $E[\dots]$ represents the expected value operator.

Since ϵ is following a standard normal distribution, $E[\epsilon] = 0$ and we get:

$$E\left[\frac{\Delta X}{X}\right] = \alpha\Delta t \quad (4.8)$$

The drift parameter α characterizes the expected rate of evolution of X per unit time. In the case of a stock price, α can be understood as the expected return per unit time on the stock. It must be noted that the expected value of the rate of variation of X is linear with respect to time.

- **Volatility σ** Let's now consider the variance of the rate of variation of X in the discrete-time model:

$$var\left[\frac{\Delta X}{X}\right] = var\left[\alpha\Delta t + \sigma\epsilon\sqrt{\Delta t}\right] \quad (4.9)$$

where $var[\dots]$ represents the variance operator.

Since only ϵ is a random variable, Equation 4.9 is equivalent to:

$$var\left[\frac{\Delta X}{X}\right] = var\left[\sigma\epsilon\sqrt{\Delta t}\right] \quad (4.10)$$

$$= \left(\sigma\sqrt{\Delta t}\right)^2 var[\epsilon] \quad (4.11)$$

Since ϵ follows a standard normal distribution, $var(\epsilon)$ is 1 and we get:

$$var\left[\frac{\Delta X}{X}\right] = \sigma^2\Delta t \quad (4.12)$$

σ characterizes the uncertainty around the evolution of X and is the rate of variance

per unit time of the rate of evolution of X . It must be noted that the variance scales with Δt : uncertainty grows as the forecast prediction is made further away in time.

The Geometric Brownian Motion can be understood as a simple Brownian Motion of the logarithm of the variable. From Equation 4.2, we get:

$$\frac{dX}{X} = \alpha dt + \sigma dz \quad (4.13)$$

$\frac{\Delta X}{X}$ is the change in the logarithm of X . Using the Ito's Lemma 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 $\sigma^2 t$. In particular, it can be noted that whereas a simple Brownian Motion may lead to negative values of the uncertainty parameter, X is always positive in a Geometric Brownian Motion (or can be maintained above a given value by shifting the threshold from 0 to another number). The Geometric Brownian Motion is illustrated in graphs c and d in Figure 4-2. The expected value of X is given by:

$$E[X(t)] = X_0 e^{\alpha t} \quad (4.14)$$

where X_0 refers to the initial value of X at $t = 0$.

In particular, if $X(t)$ is known, the variable $x = \frac{X(t+\tau)}{X(t)}$ is log-normally distributed with mean $e^{\alpha\tau}$ and variance $\sigma^2\tau$ and its probability density function is given by:

$$p_\tau(x) = \frac{1}{\sigma\sqrt{2\pi\tau}} \frac{1}{x} \exp\left\{-\frac{[\ln(x) - (\alpha - \frac{\sigma^2}{2})\tau]^2}{2\sigma^2\tau}\right\} \quad (4.15)$$

Limitations of the choice of a Geometric Brownian Motion The Geometric Brownian Motion has been chosen because it is often used in Real Options Analysis to represent the evolution of revenues or prices. This distribution is well suited to represent a process where the observed uncertainty is the sum of many independent uncertain parameters such as in the determination of the evolution of market dynamics. The increase in uncertainty as the prediction is done further back in time is also captured through the evolution of the standard deviation as \sqrt{t} .

However, the limitations of such a characterization of the market must be emphasized. In

particular, the two parameters α and σ can be difficult to estimate. In financial valuations, the drift and the volatility are determined by looking at the past evolution of the stock prices. If the underlying real asset is traded, the same process may be followed. However, in most space missions, no traded asset can be studied and the evaluation of the expected return (drift) and the uncertainty (volatility) of the market may be a difficult process.

4.1.2 Time horizon

The satellite upgrade can in some cases extend the lifetime of the satellite. In this work, the upgrade is only considered as a way to improve the satellite performance without considering the potential life extension. Therefore, the non-flexible baseline architecture and the flexible architecture are compared over the lifetime of the baseline satellite.

4.1.3 Utility and value functions

The utility of a commercial mission is evaluated through the revenues generated by the operation of the satellite. The value function is the net profit realized π , defined as the difference between revenues \mathcal{R} and costs \mathcal{C} :

$$V([t_1, t_2]) = f(\mathcal{R}[t_1, t_2], \mathcal{C}[t_1, t_2]) \quad (4.16)$$

$$= \pi([t_1, t_2]) = \mathcal{R}[t_1, t_2] - \mathcal{C}[t_1, t_2] \quad (4.17)$$

4.1.4 Decision model

Commercial space operators are assumed to aim at maximizing profits over the lifetime of the system, therefore at each point in time, the optimal alternative is the one that maximizes the future expected value over the rest of the lifetime of the system. Real Option Analysis and dynamic programming were chosen as the preferred valuation method to capture this decision model with monetary utility and value functions. The valuation process will be detailed in the next sections.

4.2 Real options valuation for maximization of future value

Dynamic programming is used to estimate the value of options in commercial space missions. The method is first explained in the simple case of a single decision point. Building

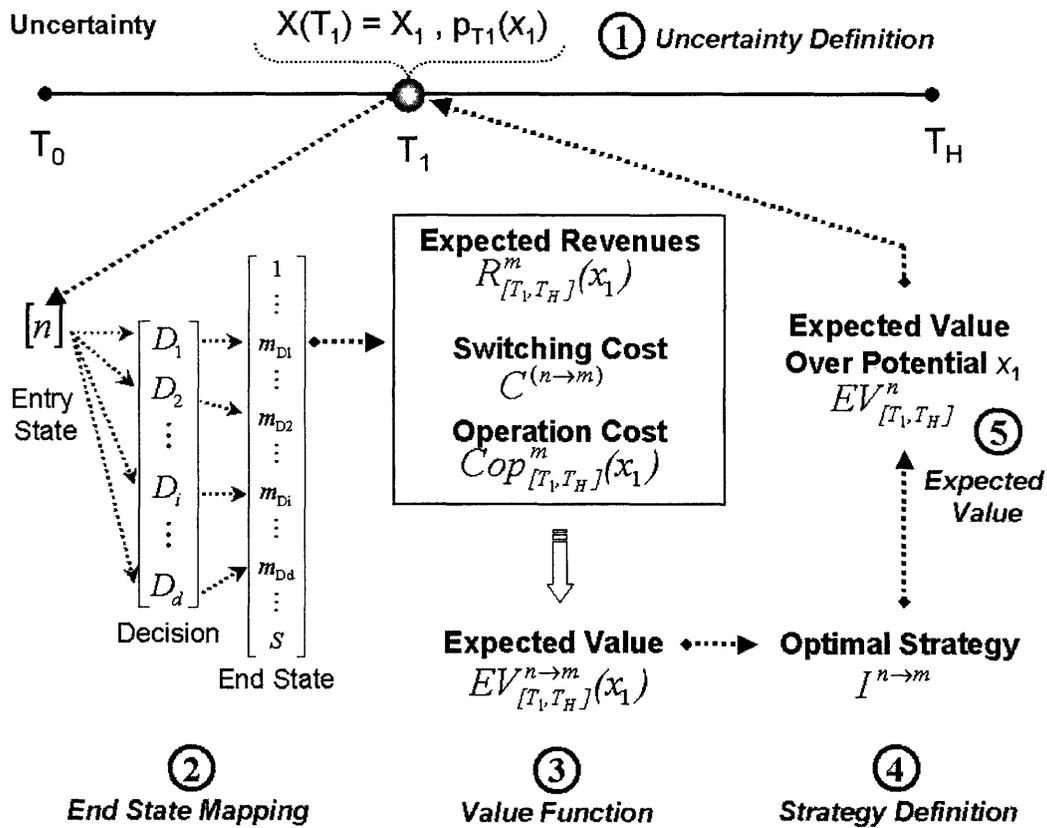


Figure 4-3: Valuation process in the case of a single decision point.

on this simple case, the valuation of compound options with multiple decision points is then described. The notations used are those presented in Section 3.4.2.

4.2.1 Simple case: one decision point

Let's consider the simple case of a single decision point T_1 at which the space operator can decide to alter the system. The various steps of the process are illustrated in Figure 4-3.

Step 1: Uncertainty definition The revenues generated after T_1 depend on the evolution of the uncertainty parameter. From the assumptions made on the distribution, the expected revenues can be calculated from the value of the uncertainty parameter at T_1 without considering the path followed by X prior to T_1 . The value of the uncertainty parameter that will be observed at T_1 is uncertain at the time T_0 . The distribution of the potential

values of X_1 is characterized by a probability density function obtained from Equation 4.15 with $t = T_0$ and $\tau = T_1 - T_0$. $X(T_0)$ is assumed to be known as the value of the uncertainty parameter currently observed. Therefore the range and probability distribution of X_1 are determined. In order to distinguish the probabilistic variable X_1 from potential values of X_1 , we will use the notation x_1 for potential values taken by X_1 .

Step 2: Decisions and end states The system entry state at T_1 is assumed to be known since there is no decision point prior to T_1 and therefore there is no possibility to alter the system between launch and T_1 . The system end state depends on the decision D_i taken at T_1 . Decisions and end states can be mapped to determine the state of the system over the period $[T_1, T_H]$ depending on the decision made. The end state is necessary to determine the revenue stream, cost and therefore the value over the time period following the decision point.

Step 3: Expected revenues, costs and expected value The revenue and cost functions can be derived for each possible end state:

- Revenues depend on the evolution of X over the period $[T_1, T_H]$. In the same process as defined in step 1, the probability density function of $X(T_1 + t)$, given the value of X at T_1 , can be derived. The function giving the expected revenues generated over the period $[T_1, T_H]$, noted $ER_{[T_1, T_H]}^m(x_1)$ can then be derived. The expected value operator refers here to an expected value over the potential evolution of X over $[T_1, T_H]$ given that the value of X at T_1 is x_1 . Therefore the expected revenues are a function of both the end state m and the actual value of X observed at T_1 .

$$ER_{[T_1, T_H]}^m(x_1) = E_X \left[\int_{T_1}^{T_H} e^{-rt} u^m(X(t)) dt \right] \quad (4.18)$$

$$= \int_{-\infty}^{+\infty} \left(\int_{T_1}^{T_H} e^{-rt} u^m(X(t)) dt \right) p(X(t)|X(T_1) = x_1) dX \quad (4.19)$$

where r represents the risk free discount rate, e^{-rt} the discounting factor for future revenues, $u^m(X(t))$ the revenue stream per unit time (which depends on the state of the system and the uncertainty parameter) and $p(X(t)|X(T_1) = x_1)$ the probability distribution of X given that x_1 is observed at T_1 . The expected value operator E_X

can be given by:

$$E_X[f] = \int_{-\infty}^{+\infty} f(X)p(X)dX \quad (4.20)$$

- The cost of switching from state n to state m is determined for each potential end state m . In this section, the operation costs have not been included in the switching costs and are shown separately. The switching costs $C^{(n \rightarrow m)}$ encompass the cost of servicing and the cost of developing and installing the replacement unit. An impossible transition from an entry state i to an end state j is eliminated by assigning an infinite cost in the matrix entry \mathcal{C}_{ij} .
- The discounted operation costs over the period $[T_1, T_H]$ must be added. The operation costs may depend on the system end state. If a constant operation cost per unit time is defined o_p^m for each state m , the discounted operation costs are given by:

$$Cop_{[T_1, T_H]}^m = o_p^m \int_{T_1}^{T_H} e^{-rt} dt \quad (4.21)$$

The expected value $EV_{[T_1, T_H]}^{n \rightarrow m}(x_1)$ can be derived from the expected revenues and the costs. Since the value function is linear we can write the value function as follow:

$$EV_{[T_1, T_H]}^{n \rightarrow m}(x_1) = ER_{[T_1, T_H]}^m(x_1) - C^{(n \rightarrow m)} - Cop_{[T_1, T_H]}^m \quad (4.22)$$

The expected value depends on the end state and the actual value x_1 observed at T_1 .

Step 4: Optimal strategy As stated, the goal of the decision maker is to maximize the expected value generated over the period $[T_1, T_H]$ knowing that x_1 is observed. This decision model is used to derive the optimal decision depending on x_1 . From the expected value $EV_{[T_1, T_H]}^{n \rightarrow m}(x_1)$ derived in step 3, for each potential end state m , we define the ranges of values x_1 for which switching to m is the optimal decision.

$$I^{n \rightarrow m} = \left\{ x_1 / EV_{[T_1, T_H]}^{n \rightarrow m}(x_1) \geq EV_{[T_1, T_H]}^{n \rightarrow l}(x_1), \forall l \neq m \right\} \quad (4.23)$$

The optimal end state can be mapped back to the corresponding optimal decision. An optimal strategy is therefore derived. The decision maker can use this strategy at T_1 . Once at T_1 , the value of X_1 will be observed and an occurrence x_1 will be seen. The $I^{n \rightarrow m}$

containing this x_i directly gives what decision should be made.

Step 5: Expected value over $[T_1, T_H]$ In order to estimate the expected value over the time horizon, the global expected value over the period $[T_1, T_H]$ must be calculated, taking into account that the decision maker will follow the optimal strategy derived in Step 4. For each x_i , the optimal decision and the corresponding expected value $EV_{[T_1, T_H]}^{n \rightarrow m}(x_1)$ is known (Step 3 and 4) as well as the probability of occurrence of x_i (Step 1). The expected value can be easily calculated:

$$EV_{[T_1, T_H]}^n = \int_{-\infty}^{+\infty} EV_{[T_1, T_H]}^{n \rightarrow m^*}(x_1) p(x_1 | X(T_0) = x_0) dx_1 \quad (4.24)$$

$$= \sum_m c \int_{I^{n \rightarrow m}} EV_{[T_1, T_H]}^{n \rightarrow m}(x_1) p(x_1 | X(T_0) = x_0) dx_1 \quad (4.25)$$

where m^* refers to the fact that the optimal decision is taken at T_1 . $EV_{[T_1, T_H]}^n$ does not depend on m or x_1 anymore.

Step 6: Initial period In order to get the total expected value of the mission, the expected value over the initial period from T_0 to T_1 must be added. The evaluation process is very similar to what has been done for the period $[T_1, T_H]$ except that there is no optimal strategy. It is assumed that the system is launched at T_0 . The probability distribution of X is calculated knowing that $X(T_0) = x_0$ using Equation 4.15. Expected revenues and operation costs are estimated over the period $[T_0, T_1]$. The expected value of the mission over the initial period $[T_0, T_1]$ is derived. The total expected value over the time horizon is the sum of the initial expected value prior to T_1 and the discounted expected value after T_1 .

$$EV_{[T_0, T_H]}^n = EV_{[T_0, T_1]}^n + e^{-r(T_1 - T_0)} EV_{[T_1, T_H]}^n \quad (4.26)$$

Flexibility value The expected value of a baseline non flexible system can be calculated. The difference between the expected value of a flexible system and the baseline expected value represents the added value of the option to service or added flexibility value.

Expected number of servicing operations The expected demand for servicing operations can be calculated from the optimal strategy. For each value x_1 , a servicing operation is demanded if servicing is the optimal strategy. The expected number of servicing operations

can then be derived using the probability distribution of X_1 .

$$E[Serv] = \int_{-\infty}^{+\infty} \delta_{Serv}(x_1) p(x_1 | X(T_0) = x_0) dx_1 \quad (4.27)$$

where

$$\delta_{Serv}(x_1) = 1 \text{ if servicing is optimal when } x_1 \text{ is observed} \quad (4.28)$$

$$= 0 \text{ if servicing is not optimal when } x_1 \text{ is observed} \quad (4.29)$$

4.2.2 Compound options: multiple decision points

It is likely that decision makers will have more than one opportunity to alter the system and that multiple decision points will be available. The extension of the previous process to multiple decision points is presented.

Differences from a single decision point model

To understand the main differences with the single decision point case, let's consider a decision point T_k that is not the first nor the last decision point.

- The entry state of the system at T_k may depend on the decisions made at the decision points prior to T_k . The consequences of prior decisions impact the state of the system at T_k .
- The optimal decision at T_k is the one that maximizes the future expected value over the period $[T_k, T_H]$. The difference with the previous case is that the system may now be altered at different points in time between T_k and T_H since other decision points exist. The expected value over $[T_{k+1}, T_H]$ will be affected by the decisions made after T_k . Therefore, the optimal strategy at the following decision points must be known in order to determine the optimal decision at T_k .

The optimal decision at T_k is dependent on other decisions. The principle of the multi decision point process is to adapt the process in order to solve these dependency issues and reuse the simple case of a single decision point.

From a single to a multiple decision point model

The multiple decision model is characterized by three main principles that allow to solve the dependency issues.

Set of entry states The issue concerning the path followed prior to T_k can be solved by carefully defining a list of entry states that captures the complete set of possible system states resulting from earlier decisions. It must be noted that the set of entry states does not represent all the potential paths leading to T_k . The set of potential entry states must be limited to the characteristics that are necessary to calculate the expected value over the next period. As an example, let's consider the option to extend a satellite lifetime using on-orbit servicing. A decision point exists each time the satellite reaches the end of its lifetime. Let's further assume that the satellite cannot be reactivated if it has been dormant for one period. In order to evaluate the value of the mission over $[T_k, T_H]$, one needs to know whether the satellite has been maintained until T_k or if the satellite is already dormant and cannot be reactivated. However, one does not require the exact sequence of decisions from T_0 to T_k . Therefore, only two entry states are necessary to describe the consequences of prior decisions: active or dormant satellite.

Bellman equation The valuation process is adapted to reuse the simple decision point method by decoupling the calculation at the period $[T_k, T_{k+1}]$ from the calculation over the rest of the time horizon through the Bellman equation. The Bellman equation states that the expected value over the period $[T_k, T_H]$ can be divided in two parts: the expected value over the period $[T_k, T_{k+1}]$ and the period $[T_{k+1}, T_H]$.

$$EV_{[T_k, T_H]} = EV_{[T_k, T_{k+1}]} + e^{-r(T_{k+1}-T_k)} EV_{[T_{k+1}, T_H]} \quad (4.30)$$

When considering the entry state and the different possible end states we get:

$$EV_{[T_k, T_H]}^{(n \rightarrow m)} = EV_{[T_k, T_{k+1}]}^{(n \rightarrow m)} + e^{-r(T_{k+1}-T_k)} EV_{[T_{k+1}, T_H]}^m \quad (4.31)$$

Backward process Since the decision model considers the optimization of future value, the consequence of one strategy on the value at later periods must be taken into account. The valuation must be conducted at the periods following T_k before considering the decision

point T_k . Therefore, a backward process is used, starting at the last decision point and proceeding backwards in time towards the first decision point. As a consequence, the second part of the right side of Equation 4.31 is known when the calculation is done at T_k . Only the first part of the right side of Equation 4.31 must be evaluated. This process is similar to solving a single decision point model. The valuation process in the case of multiple decision points is described in more details in the following paragraphs and is illustrated in Figure 4-4 and Figure 4-5

Last decision point T_{N-1}

The valuation process starts at the last decision point T_{N-1} (T_N being the end of the time horizon, no decision is made at that point). The valuation at T_{N-1} is similar to the one decision point model as illustrated in Figure 4-4. For each possible system entry state:

- Decisions are mapped to end states of the system.
- For each decision, the expected value function over the period $[T_{N-1}, T_N]$ is defined. This function depends on the value of the uncertainty parameter observed at T_{N-1} .
- The optimal strategy is then derived by choosing the decisions that maximize the expected value over $[T_{N-1}, T_N]$. The sets $I_{N-1}^{n \rightarrow m}$ are defined, corresponding to the range of values x_{N-1} for which a switch from n to m is optimal.

Those steps are similar to the single decision point process. However, the final expected value over $[T_{N-1}, T_N]$ cannot yet be derived since the probability distribution of X_{N-1} will depend on the value x_{N-2} observed at T_{N-2} .

From decision point T_{k+1} to decision point T_k The backwards process proceeds from a decision point T_{k+1} to the next step at the previous decision point T_k . The process is illustrated in Figure 4-5.

- **X_{k+1} probability distribution** For each value x_k of the uncertainty parameter observed at T_k , the probability distribution of X_{k+1} can be determined, $p(X(T_{k+1}) = x_{k+1} | X(T_k) = x_k)$, using Equation 4.15. This probability distribution will be used to calculate the expected value over $[T_{k+1}, T_N]$ knowing that the uncertainty parameter observed at T_k is x_k .

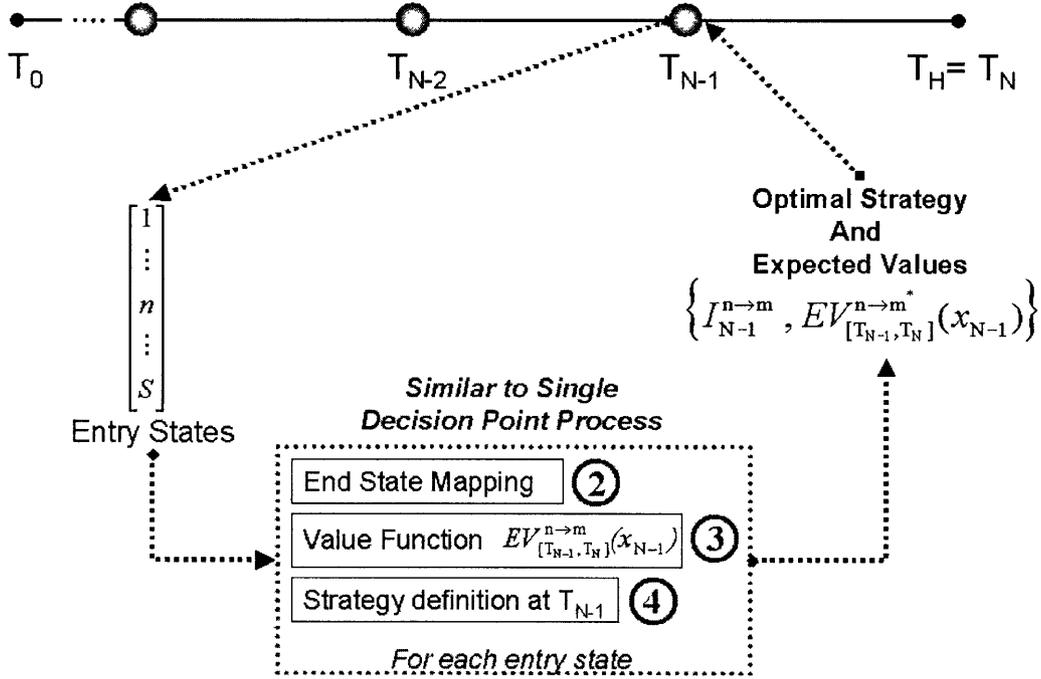


Figure 4-4: Valuation process at T_{N-1} in the case of a multiple decision point model.

- End state mapping** For each entry state n , decisions D_i made at T_k are mapped to the corresponding system end state m_i^n . The end state of the system at the decision point T_k is the entry state of the system at the next decision point T_{k+1} . This will allow tracking the consequences of a decision made at T_k on future value and reusing the results of the calculation at T_{k+1} .
- Expected value $EV_{[T_k, T_N]}^{n \to m}(x_k)$ calculation** As stated by the Bellman equation, the expected value $EV_{[T_k, T_N]}^{n \to m}(x_k)$ can be separated in two parts: the expected value generated over $[T_k, T_{k+1}]$ and the expected value over the rest of the time horizon $[T_{k+1}, T_N]$. The expected value $EV_{[T_k, T_{k+1}]}^{n \to m}(x_k)$ is calculated as described in Step 3 of the single decision point process. The expected value $EV_{[T_{k+1}, T_N]}^m(x_k)$ is calculated using the probability distribution of X_{k+1} and the optimal strategy defined at T_{k+1} in the previous step. $EV_{[T_{k+1}, T_N]}^m$ must be discounted at the risk free rate r to take into account the time value of money.

$$EV_{[T_k, T_N]}^{n \to m}(x_k) = EV_{[T_k, T_{k+1}]}^{n \to m}(x_k) + e^{-r\Delta t} EV_{[T_{k+1}, T_N]}^m(x_k) \quad (4.32)$$

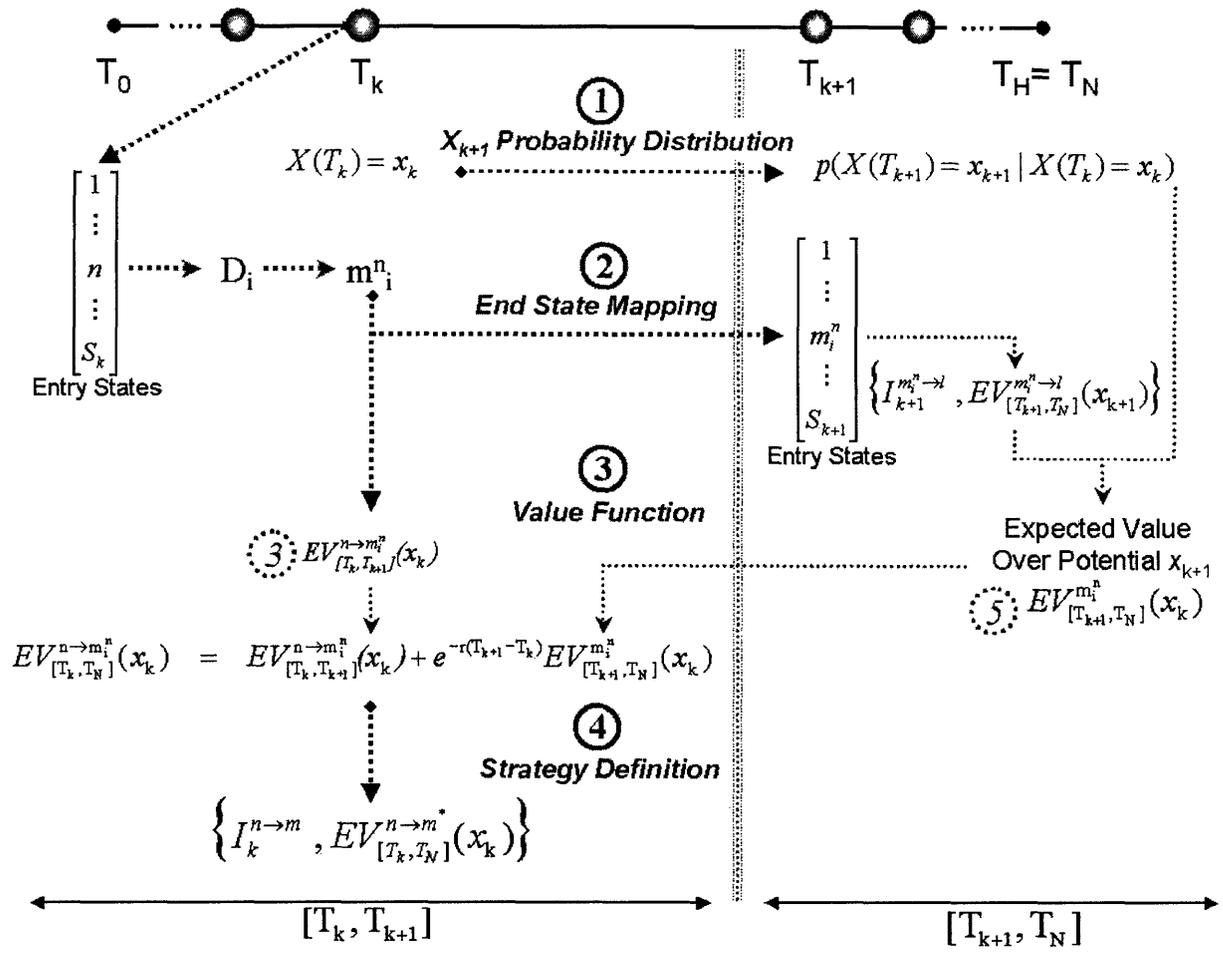


Figure 4-5: Valuation process at a decision point T_k within the time horizon. The numbers circled with a dashed line refer to the corresponding steps in the single decision point process.

with

$$\begin{aligned}\Delta t &= T_{k+1} - T_k \\ EV_{[T_k, T_{k+1}]}^{n \rightarrow m}(x_k) &= ER_{[T_k, T_{k+1}]}^m(x_k) - C^{(n \rightarrow m)} - COP_{[T_k, T_{k+1}]}^m \\ EV_{[T_{k+1}, T_N]}^m(x_k) &= \sum_l \int_{I_{k+1}^{m \rightarrow l}} EV_{[T_{k+1}, T_N]}^{m \rightarrow l}(y) p(y|X(T_k) = x_k) dy\end{aligned}$$

- **Optimal strategy** The optimal strategy can be derived using the expected value function $EV_{[T_k, T_N]}^{n \rightarrow m}(x_k)$ as explained in Step 4 in the single decision point process. The sets $I_k^{n \rightarrow m}$ are defined, corresponding to the range of values x_k for which a switch from n to m is optimal.

Initial period The valuation process is carried out up to the first decision point. The calculation for the initial period is similar to the single decision point process. The total expected value of the mission at T_0 can be estimated $EV_{[T_0, T_N]}^1$.

4.3 Numerical analysis of commercial missions

The numerical implementation of the valuation process previously described uses a discrete approximation of the Geometric Brownian Motion called the binomial model. The construction of the binomial tree representing the evolution of the uncertainty parameter is first described before presenting the discrete numerical model used for commercial missions. The method described is based on the log-transformed binomial lattice method presented by Trigeorgis [35] and has been applied to the valuation of space systems by Lamassoure [16].

4.3.1 Uncertainty representation: Binomial model

Binomial Model

In the binomial model, the evolution of the uncertainty parameter over time is represented in a tree. The construction of the binomial tree is detailed in the following paragraphs.

Log-transformed process If X follows a Geometric Brownian Motion, the variable $Y = \ln(X)$ follows a Brownian Motion with a drift $\alpha - \frac{\sigma^2}{2}$ and volatility σ (Section 4.1.1). This substitute variable Y is used to ensure a better convergence of the discrete model.

Construction of the binomial tree As showed in Section 4.1.1, the continuous Brownian Motion can be understood as the limit of a random walk process when the step size tends to zero. The discrete numerical model uses the discrete distribution of Y obtained from the approximation of a random walk.

The time horizon T_H is discretized with time steps Δt . In the binomial model, the parameter Y can either go up or down by an amount ΔH_Y during one time step Δt . The probability of a step up (respectively step down) is p (respectively $1 - p$). p and ΔH_Y are defined so as to conserve the mean and the variance of the initial continuous Brownian Motion. The potential values of Y over the time period considered form a tree called the binomial tree as illustrated in Figure 4-6. The tree is recombining since a step down followed by a step up leads to the same value of Y than a step up followed by a step down. The accuracy of the approximation depends on the number of time steps used: the more time steps, the finer the grid of Y and therefore the closer to a continuous distribution. The probability p of a step up and the size of a step ΔH_Y can be determined by ensuring the conservation of the mean and the variance of the Brownian Motion:

$$\begin{cases} E[dY] = p\Delta H_Y + (1-p)(-\Delta H_Y) = (\alpha - \frac{\sigma^2}{2})dt \\ var[dY] = [p\Delta H_Y^2 + (1-p)(-\Delta H_Y)^2] - E[dY]^2 = \sigma^2dt \end{cases} \quad (4.33)$$

$$\Leftrightarrow \begin{cases} \Delta H_Y = \sqrt{\sigma^2\Delta t + (\alpha - \frac{\sigma^2}{2})^2 \Delta t^2} \\ p = \frac{1}{2} \left(1 + \frac{(\alpha - \frac{\sigma^2}{2})\Delta t}{\Delta H_Y} \right) \end{cases} \quad (4.34)$$

The binomial tree can be represented in a matrix Y_{ij} , the column $[Y_j]$ being the vector of the potential values of Y_j at the time $j\Delta t$ in descending order. At a point in time $j\Delta t$:

- The value of X is the logarithm of the value of Y read in the tree: $x_{ij} = \ln(y_{ij})$.
- The probability of observing $x_{ij} = \ln(y_{ij})$ knowing that the last observation was x_0 at T_0 is: $\binom{j-1}{i-1} p^{j-i}(1-p)^{i-1}$.

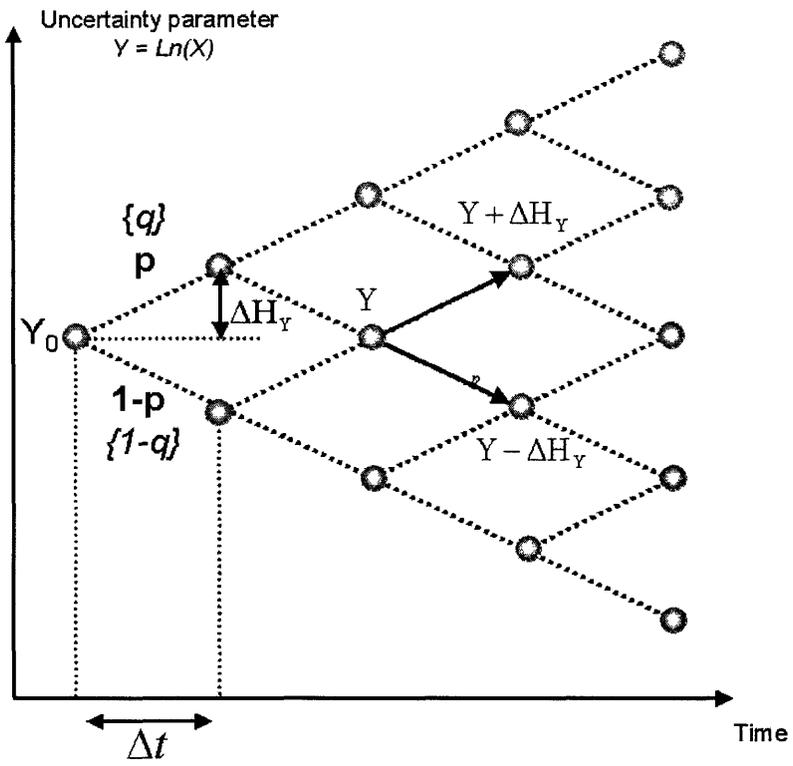


Figure 4-6: Binomial tree representing the distribution of Y over the time horizon.

- The probability of observing $x_{ij} = \ln(y_{ij})$ knowing that the last observation was $x_{lk} = \ln(y_{lk})$ at $T_k = k\Delta t < T_j$ is:
$$\binom{j-k}{i-l} p^{j-k-(i-l)} (1-p)^{i-l}.$$

Risk neutral probabilities In the valuation process, we use the risk neutral probability q as introduced in Section 3.3.2 to be able to discount the cash flows at the risk free rate r . The risk neutral probability is not a real probability but is used as an equivalent for p . This corresponds to having a “probability” q (respectively $1 - q$) for a step up (respectively a step down) in the binomial tree.

Uncertainty tree and decision tree

The binomial tree represents the evolution of the uncertainty parameter over time. It corresponds to the chance nodes of a decision tree. However, the possible decisions available to the decision maker are not represented in the binomial tree which is only the uncertainty part of a decision tree. The relation between the binomial tree and the decisions is illustrated in Figure 4-7. The combination of the two trees shown in Figure 4-7 is the decision tree of Decision Tree Analysis (DTA). It must be noted that all nodes in the binomial tree may not correspond to decision points. The valuation process will be presented by walking through the binomial tree back in time and not by solving the tree of decisions.

4.3.2 Valuation process

Uncertainty and matrix of switching costs

The binomial tree is first constructed and represented in a matrix $\{y_{ij}\}$ where a column j represents a point in time $j\Delta t$ and y_{ij} is the i th highest value of Y at time $j\Delta t$. The corresponding matrix of the uncertainty parameter X is $x_{ij} = \ln(y_{ij})$.

The potential system states are defined before calculating the matrix of switching costs $\mathcal{C}^{(n \rightarrow m)} = (C_{ij})$: C_{ij} is the cost of switching from state i to state j .

Last decision point

At the last decision point, the revenues are calculated over the period $[T_{N-1}, T_N]$ for all potential end states and value of X_{N-1} . The resulting value matrix is of size $(N - 1) \times S$. The columns represent the potential end states and the rows the possible values of X_{N-1} :

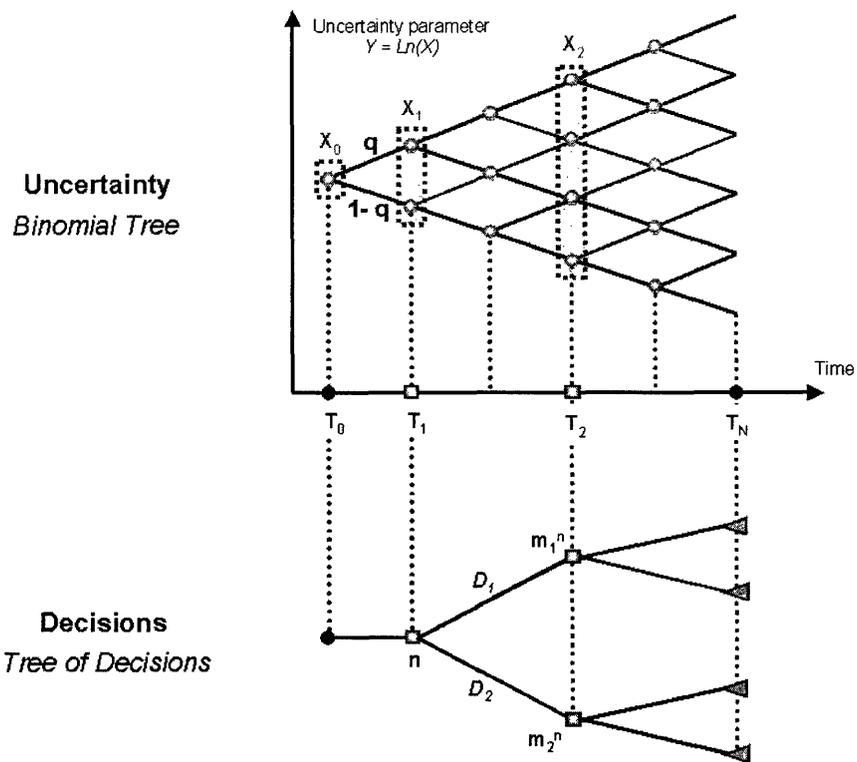


Figure 4-7: Relation between the binomial tree representing the evolution of uncertainty over time and the decisions available to the decision maker.

$EV_{[N-1,N]}^n(i, j) = EV_{[N-1,N]}^{n \rightarrow j}(x_{i,N-1})$. The optimal strategy is defined by choosing the end state that maximizes the value in each row of $EV_{[N-1,N]}^n$. The process is illustrated in Figure 4-8.

Induction process

The process at a decision point T_k is illustrated in Figure 4-10 in the particular case of a binomial tree in which all nodes are decision points. The value over the period $[T_k, T_{k+1}]$ is calculated as for a single decision point model. The value over the period $[T_{k+1}, T_N]$ is calculated using the risk neutral probabilities q of a step up (respectively $1 - q$ of a step down) in the binomial tree and using the risk free rate r to discount future profits. If all nodes are not decision points in the binomial tree, the calculation of the expected value over $[T_{k+1}, T_N]$ is slightly more complex since the probability distribution of X_{k+1} is not given by q and $1 - q$ as illustrated in Figure 4-9 and Section 4.3.1. The discount factor must also be adapted since more than one time step has elapsed. The expected value calculation and the discounting from $T_{k+1} = T_k + \Delta K \Delta t$ to T_k can be done jointly by defining a matrix $A_{k \leftarrow (k+\Delta K)}$ [16] as follow:

$$A_{k \leftarrow (k+\Delta K)}(i, j) = e^{-r\Delta K \Delta t} \begin{pmatrix} \Delta K \\ j - i \end{pmatrix} q^{\Delta K - (j-i)} (1-q)^{j-i} \quad \forall j \in \{i, \dots, i + \Delta K\} \quad (4.35)$$

The induction process becomes:

$$EV_{[T_k, T_N]}^{n \rightarrow m} = EV_{[T_k, T_k + \Delta K \Delta t]}^{n \rightarrow m} + A_{k \leftarrow (k+\Delta K)} EV_{[T_{k+1}, T_N]}^{*m} \quad (4.36)$$

The backward process can be computed up to the first decision point to get the expected value of the mission over the entire time horizon, taking into account that at each decision point the optimal strategy is followed.

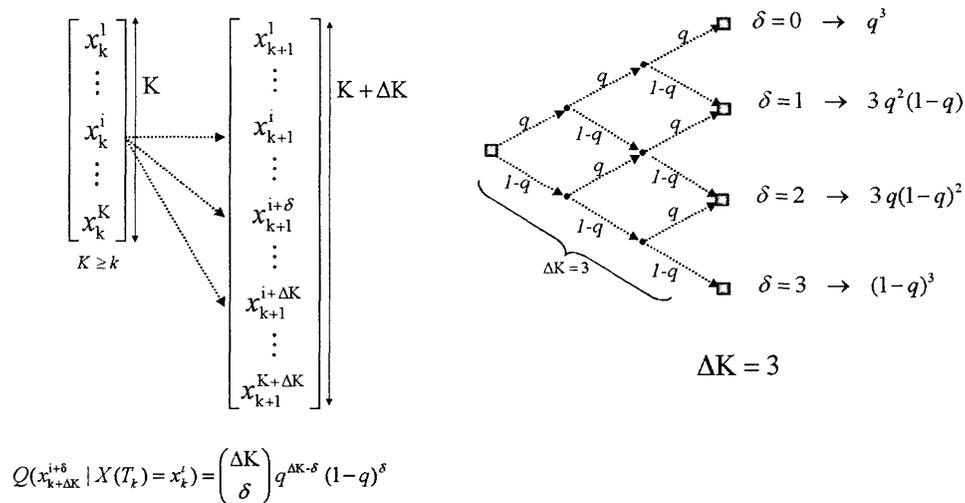


Figure 4-9: Probability distribution of X_{k+1} knowing x_k is observed at T_k .

4.4 Application to a commercial mission facing uncertain revenues

4.4.1 Presentation and objectives

The upgrade of a commercial satellite is assumed to be driven by the desire to increase the revenues generated by the mission. For a first application of the valuation method to satellite upgrade, we consider a commercial mission facing uncertain revenues. Upgrading is chosen if the expected added profits generated over the rest of the lifetime overcome the cost and risk of servicing. The potential effect of the upgrade on the revenue stream depends on the mission considered and must be carefully modelled to get precise results. However, in this first application, the potential increase in revenues due to the upgrade is left as a parameter to get first insights on the potential value of upgrading. The simplicity of this first case makes it a good candidate for investigating the main drivers of the value of on-orbit servicing for satellite upgrade. The main questions to be studied are:

- How large is the flexibility value offered by the option to upgrade?
- In which conditions does satellite upgrade seem valuable?
- In which conditions does on-orbit servicing appear as the preferred option to upgrade

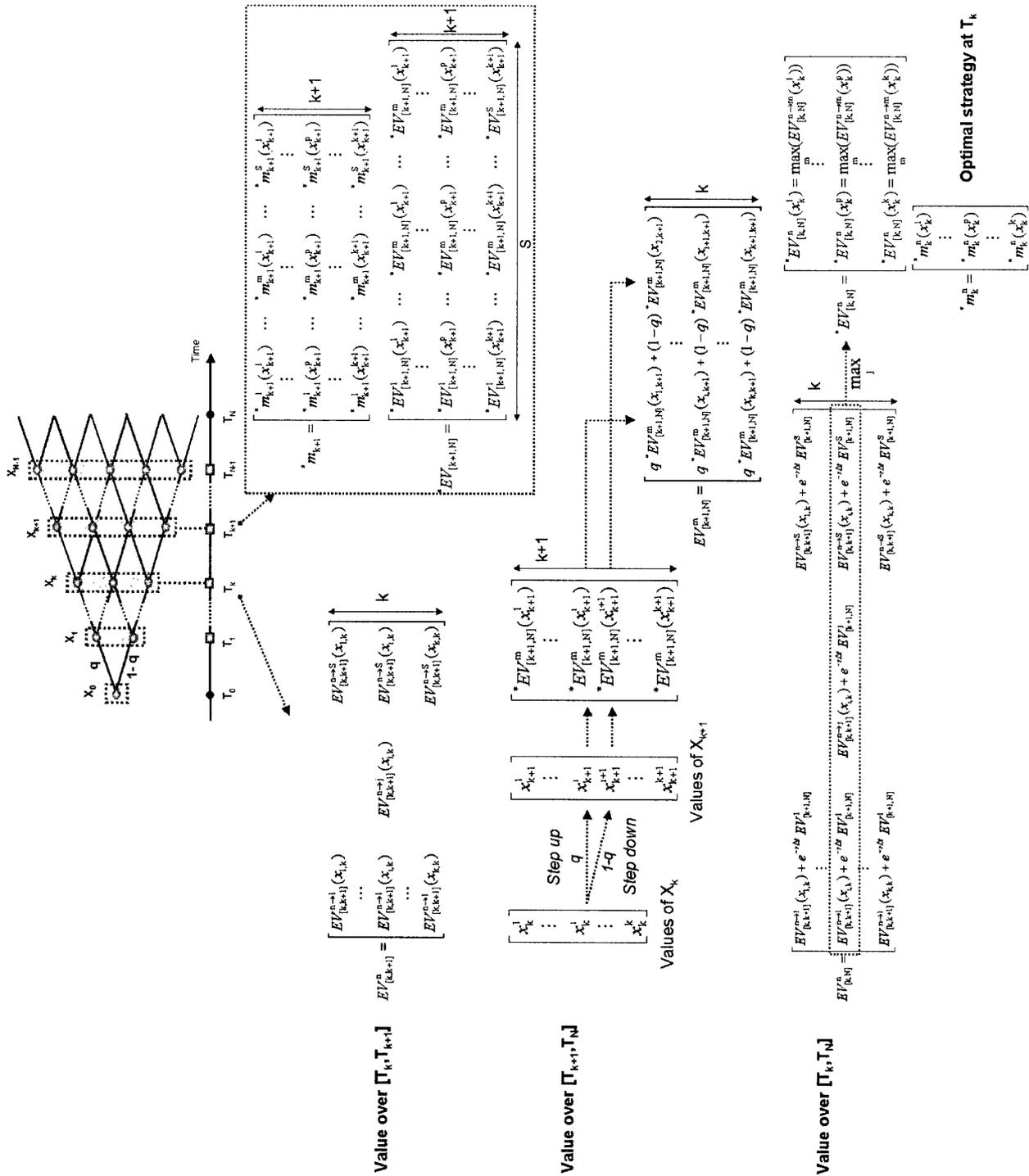


Figure 4-10: Numerical process at a decision point T_k for an entry state n in the particular case of a binomial tree in which all nodes correspond to decision points.

a satellite?

- What are the main drivers of the value of satellite upgrade and what are the effects of some main parameters such as market volatility or the risk and price of a servicing operation?

4.4.2 Assumptions and model description

Uncertainty parameter X

Market forecasts are done to predict what level of revenues are expected over the period of operation of the satellite. The forecasted revenues are noted \mathcal{M}_f . However, the dynamics of the market the satellite is serving is difficult to predict and therefore the actual revenues, noted \mathcal{M} , may differ from the forecast.

The uncertainty parameter is chosen as the ratio of the actual revenues to the forecasted revenues:

$$X(t) = \frac{\mathcal{M}(t)}{\mathcal{M}_f(t)} \quad (4.37)$$

Since the uncertainty is linked to unpredictable changes in the market, it is assumed to be external to the operator decision. The same uncertainty applies to revenues generated with or without an upgrade and the uncertainty parameter is not affected by the decision made. The uncertainty parameter is further assumed to follow a Geometric Brownian Motion with drift α and volatility σ .

Baseline and flexibility

The baseline architecture chosen as a reference for the estimation of the flexibility value is a non-flexible satellite that cannot be upgraded (it can neither be serviced or replaced). In the case of a flexible architecture, three decisions are available to the space operator:

1. Status Quo: The satellite is not altered.
2. Service: The satellite is upgraded using on-orbit servicing.
3. Replace: A replacement satellite is launched that incorporates the upgrade and is expected to produce the same level of revenues as a serviced satellite.

The system can be described with three states: State 1: initial performance; State 2: upgraded performance through servicing; State 3: upgraded performance through replacement. The option to abandon is not included in this model for any of the architectures.

Revenue calculation and effect of the upgrade

The forecasted revenues per year for a baseline satellite are assumed to be constant through the satellite lifetime: $\mathcal{M}_f^1 = \mathcal{M}_0$. A satellite upgrade increases the forecasted revenues that the satellite is expected to generate per year by a factor η . This represents the installation of a new technology or an increase in capacity by installing more transponders for example.

$$\mathcal{M}_f^2 = \mathcal{M}_f^3 = \eta \mathcal{M}_f^1 \quad (4.38)$$

where \mathcal{M}_f^2 represents the forecasted revenues for a serviced satellite and \mathcal{M}_f^3 the forecasted revenues for a new satellite.

With the definition of the uncertain parameter chosen, the calculation of the expected revenues generated over a period $[T_k, T_{k+1}]$ can be simplified.

$$ER_{[T_k, T_{k+1}]}^m(x_k) = E \left[\int_{T_k}^{T_{k+1}} e^{-rt} \mathcal{M}_f^m X(T_k + t) dt \right] \quad (4.39)$$

$$= \mathcal{M}_f^m \int_{T_k}^{T_{k+1}} e^{-rt} \left(\int_{-\infty}^{+\infty} \frac{X(T_k + t)}{X(T_k)} x_k dx_k \right) dt \quad (4.40)$$

$$= \mathcal{M}_f^m x_k \int_{T_k}^{T_{k+1}} e^{-rt} E \left[\frac{X(T_k + t)}{X(T_k)} \right] dt \quad (4.41)$$

$$= \mathcal{M}_f^m x_k \int_{T_k}^{T_{k+1}} e^{-rt} e^{\alpha t} dt \quad (4.42)$$

$$= \mathcal{M}_f^m x_k \int_{T_k}^{T_{k+1}} e^{(\alpha-r)t} dt \quad (4.43)$$

The function $\mathcal{IR}_\tau^m = \mathcal{M}_f^m \int_0^\tau e^{(\alpha-r)t} dt$ can be evaluated and is independent from the uncertainty observed or the decision point considered. It represents the incremental revenues generated over a period τ according to the forecast. The actual revenues generated over the period $[T_k, T_{k+1}]$ are calculated as the product of the incremental revenue function and the value x_k of the uncertainty parameter observed at T_k .

$$ER_{[T_k, T_{k+1}]}^m(x_k) = x_k \mathcal{IR}_{(T_{k+1}-T_k)}^m \quad (4.44)$$

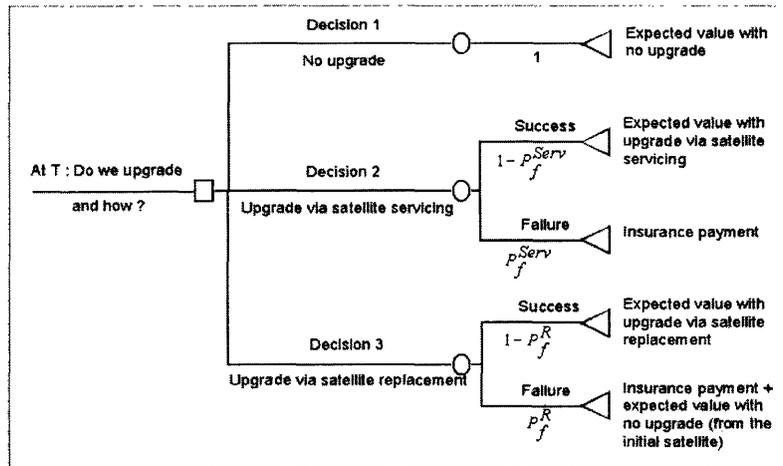


Figure 4-11: Decision tree illustrating the consideration of risk in the model.

Risk of failure

The risk of a servicing operation is often a strong argument held against on-orbit servicing and is a critical parameter in the development of on-orbit servicing. Therefore risk must be included in the analysis. Risk is taken into account for both the launch of a new satellite and for a servicing operation by considering an insurance payment and the loss of revenues in case of failure.

A failure is assumed to be catastrophic. In the case of a servicing mission, the failure leads to the loss of the satellite serviced and no further revenues are generated. In the case of a replacement launch, the replacement satellite is lost but the former satellite is assumed to be still operational providing revenues.

An insurance payment is included when a servicing operation is demanded or for a new launch. The insurance payment is the product of the probability of occurrence of a catastrophic failure and the amount insured that is paid out in case of failure. In the case of a satellite launch (initial and replacement launch), the amount insured is the cost of the satellite launched. In the case of a servicing operation, the amount insured is the sum of the depreciated value of the satellite at the time of the decision and the loss of revenues over the rest of the life of the satellite calculated on the basis of the forecasted revenues.

In addition, the effect of a failure on the revenue stream is captured by considering the expected value over the different outcomes, success or failure, of the upgrade mission. The process is captured in the decision tree shown in Figure 4-11.

Additional assumptions

Only one decision point at time T is considered in this first model. The initial satellite is assumed to be designed to be serviceable and the impact of designing for serviceability is not included: the initial cost of designing and launching the satellite is the same for the baseline and the flexible architectures. The model assumes a pre-launch operation period of 2 years between the decision to launch is made and the actual launch. For each satellite launch, satellite and launch costs are spread evenly over the pre-launch operation period. Calculation of the profits include a 40% corporate tax rate on revenues as commonly used in industry. A linear depreciation of the value of the satellite over its lifetime is chosen. A servicing operation is assumed to be completed almost immediately after the decision to service is made. If on-orbit servicing is chosen, the upgrade impacts the revenue stream starting from the period the decision to service is made. On the contrary, an upgrade via a replacement launch impacts the revenue stream only once the new satellite is in orbit, after the 2-year pre-launch period. The cost of servicing is incurred at the time the decision is made whereas the cost of a replacement launch are spread evenly over the pre-launch period.

On-orbit servicing and satellite replacement

In this model, the decision maker is faced with the decision to upgrade the system or not but also with the choice of how to implement the upgrade most efficiently. On-orbit servicing and satellite replacement can be compared according to the four criteria distinguished in Section 2.5. The impact of the model assumptions on the relative attractiveness of on-orbit servicing and satellite replacement are summarized in Table 4.1.

4.4.3 Results

The general assumptions chosen for the results presented are summarized in Table 4.2.

Dynamic strategy

It has been argued that a dynamic framework should be adopted to account for the managerial flexibility offered by on-orbit servicing. The advantage of a dynamic valuation method can be understood by looking at the optimal strategy derived at the decision point

Criteria	On-orbit servicing	Satellite replacement
Scope of upgrade	$\eta\mathcal{M}_f^1$	$\eta\mathcal{M}_f^1$
	Same upgrade effect on revenues	
Responsiveness	Immediate	2-year delay
	2-year advantage for on-orbit servicing	
Initial sat cost	C_{IOC}	C_{IOC}
Upgrade cost	$C_{Serv} + C_{RepUnit} + C_{Ins}^{Serv}$	C_{IOC}
	No penalty for designing for serviceability	
	Advantage depends on servicing cost and servicing risk	
Risk	P_f^{Serv}	P_f^R
	Advantage depends on servicing risk	

Table 4.1: Impact of model assumptions on the relative attractiveness of on-orbit servicing and satellite replacement.

Numerical Assumptions

Parameter	Description	Value
T_H	Time horizon	15 years
T	Decision point	2 years after launch
C_{Sat}	Satellite cost	\$95M
o_p^m	Operation costs	10% of forecast revenues per year
C_{Launch}	Launch cost	\$97.5M
T_L	Pre-launch operation period	2 years
P_f^R	Launch failure rate	15% (*)
$\mathcal{M}_f^1 = \mathcal{M}_0$	Forecast revenues for non upgraded satellite	\$52M
α	Drift	5.39%
σ	Volatility	10%
$C_{RepUnit}$	Replacement unit cost	\$2M
r	Risk free discount rate	5.39%

Table 4.2: Numerical assumptions for the study of a commercial mission facing uncertain revenues. (*) Current launch failure rates are estimated at about 5%. A figure of 15% has been chosen to reflect the high prices of insurance coverage that amount to about 16% to 20% of the satellite value [37].

T shown in Figure 4-12. The optimal decision is shown on the z axis. Each line represents a strategy which provides the optimal decision to make depending on the value of the uncertainty parameter observed at T . Various strategies are shown for different servicing costs. It must be noted that the optimal decision depends on the value of the resolution of the uncertainty parameter illustrating that decision makers will take into account the information they have to make a better choice. A traditional valuation would assume a fixed decision whatever the value of X observed at T .

Decision to upgrade For a cost of servicing below \$100 million, the decision maker always decide to upgrade, whatever the resolution of the uncertainty. The actual added revenues generated by the upgrade always offset the minimum cost to upgrade (which is using on-orbit servicing). A cost of \$100 million corresponds to the servicing cost for which the total additional costs of upgrading (including the cost of the servicing operation, the cost of the upgrade unit and the higher operational costs of an upgraded satellite) are equivalent to the additional benefits that can be gained from an upgrade in the worst case, when the lowest value of the uncertainty parameter is observed at T . As the minimum cost of upgrading increases with the increase of the servicing cost, upgrading is not optimal for the lowest values of X . If the observed value of X is low and suggests low actual revenues, the expected value of the actual revenues does no offset the minimum cost to upgrade.

Method chosen to upgrade The optimal method for upgrading depends on both the cost of a servicing operation and the value of the uncertainty parameter observed at T . On-orbit servicing appears more appealing for low values of the servicing cost and for high values of the uncertainty parameter. For a cost of servicing below \$160 million, it is cheaper to service than to replace the satellite therefore on-orbit servicing is the optimal method to upgrade the satellite. For a cost of servicing above \$220 million, the cost of servicing is much higher than the cost of replacing the satellite and the replacement option is the optimal method to upgrade. However, in between these two extremes, the optimal upgrade method depends on the value of X observed at T . Replacement is optimal for low values of $X(T)$ while on-orbit servicing is optimal for high values of $X(T)$. This relates to the responsiveness of on-orbit servicing compared to launching a new satellite. Servicing is more expensive than replacing the satellite when taking into account the cost of servicing, the

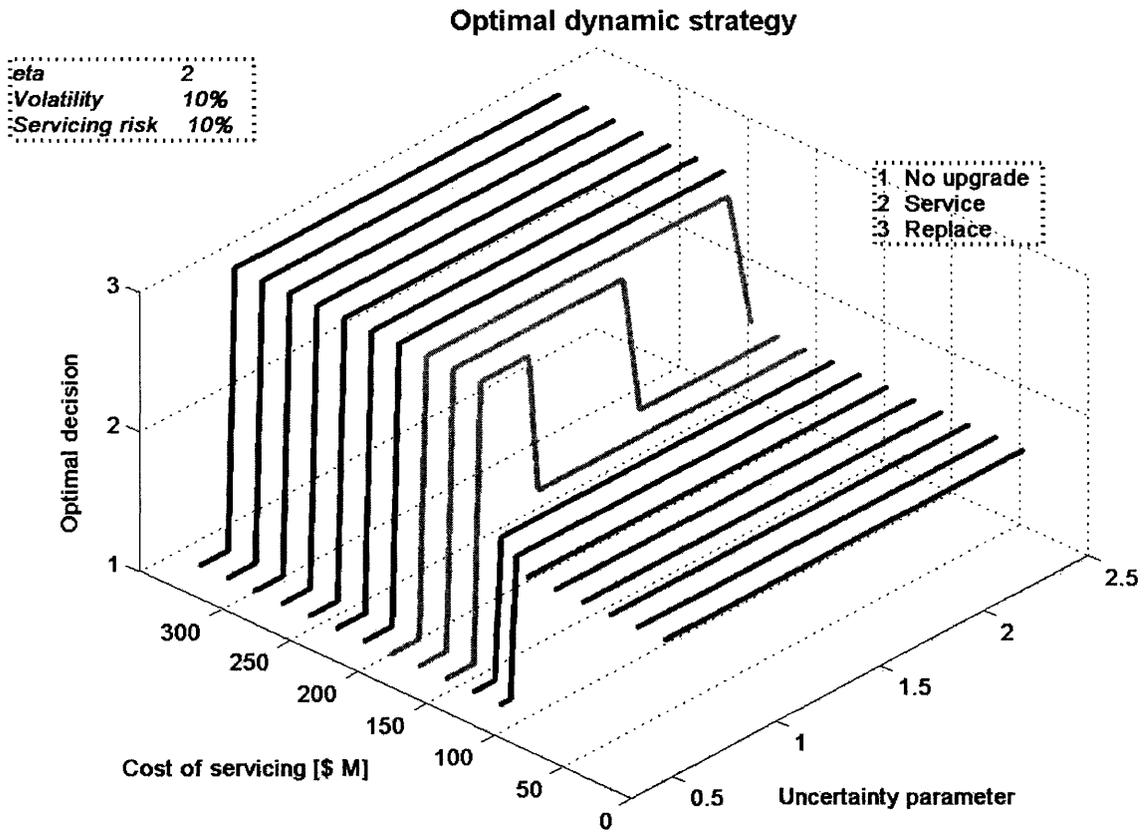


Figure 4-12: Illustration of a dynamic strategy.

insurance cost and the cost of the replacement unit. However, if the satellite is replaced, the upgrade is only implemented two years after the decision is made whereas a serviced satellite can immediately generate higher revenues. As X observed at T increases, the added actual revenues generated during the pre-launch period is high enough to offset the additional cost of on-orbit servicing compared to a satellite replacement.

This example illustrates the importance of a dynamic valuation method that accounts for the fact that an operator will use the information available about the market at the time of decision to make an optimal choice. The higher responsiveness offered by on-orbit servicing is an advantage over the replacement option. A dynamic valuation method captures the added value of this managerial flexibility. Because traditional valuation methods assume a fixed strategy, they underestimate the value of the mission as illustrated in Figure 4-13. The

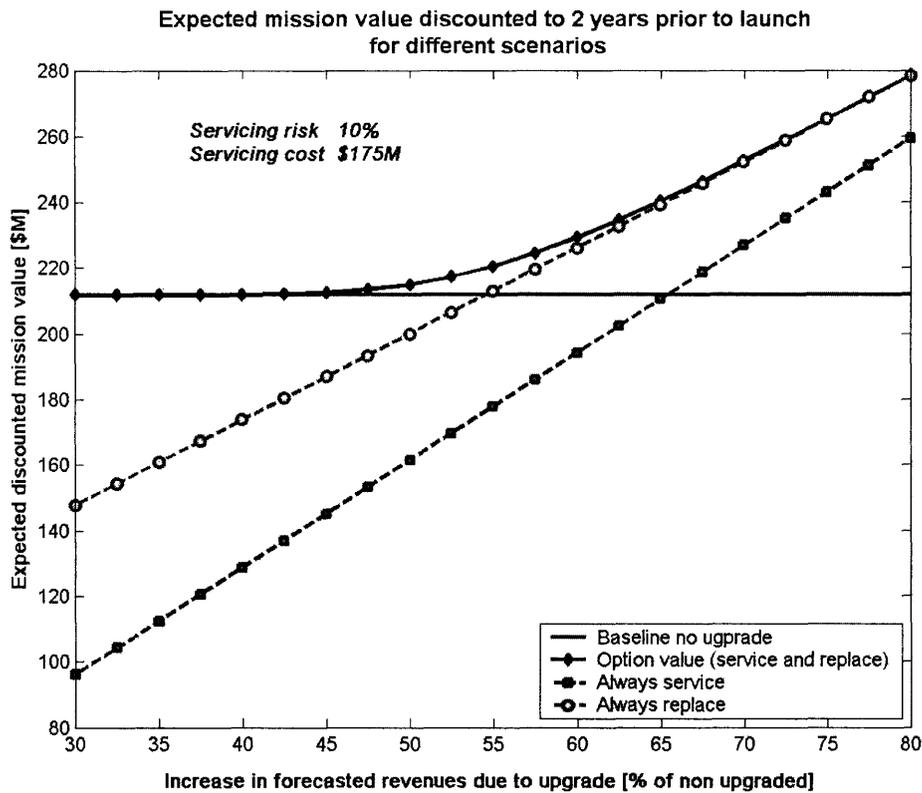


Figure 4-13: Flexibility value overlooked by static valuation methods.

expected mission value is shown as a function of the impact of the upgrade on forecasted revenues for different scenarios. Three scenarios correspond to fixed strategies, which are to never upgrade, to always service and to always replace the satellite. The value of any fixed strategy corresponds to an NPV calculation. Their value is compared with the value of a flexible strategy in which managers can decide at T what is the optimal decision to make depending on the state of the market. The flexible strategy always offers a higher value than any of the three fixed strategies. If there is a dominant strategy, optimal for any market demand level, the flexible and the non-flexible dominant strategies are equivalent. However, if there is no dominant strategy and the decision depends on the state of the market that can be observed at the time of the decision, any fixed strategy will be suboptimal. The value of managerial flexibility can be evaluated as the additional value of a flexible strategy in comparison to any of the three non-flexible scenarios.

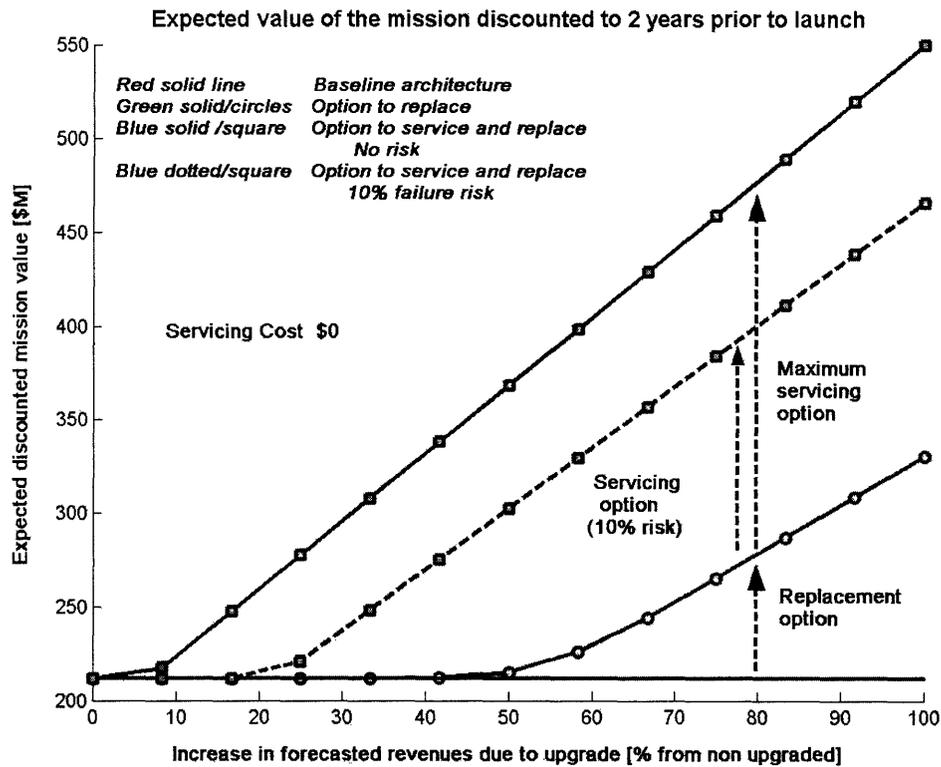


Figure 4-14: Servicing and replacement option values as a function of the increase in forecasted revenues due to the upgrade.

Flexibility value

The value of the option to upgrade is the difference between the baseline expected value and the expected value for a flexible architecture. Two different options are available: the option to upgrade using on-orbit servicing and the option to upgrade by replacing the satellite. The value of these different options are illustrated in Figure 4-14 for a cost of servicing of \$0.

The value of upgrading can be a significant part of the total expected value of the mission. For a 50% increase in forecasted revenues after upgrade, the maximum value of the option to upgrade (for a servicing cost of \$0 and a servicing risk of 0%) accounts for 42.5% of the total expected value. As the risk of servicing increases, the value of the option to service decreases. For a servicing risk of 10% the option to upgrade accounts for 30% of the total expected mission value.

Effect of the parameter η

As illustrated in Figure 4-14, the higher the increase in revenues due to the upgrade, the higher the value of the option to upgrade (both for the option to service and to replace). It can be noted that a minimum increase in forecasted revenues is required to offset the cost of the upgrade. When the risk of a servicing operation increases from 0% to 10%, the upgrade must at least increase the forecasted revenues by 17% to offset the risk of servicing the satellite. Risk appears as a key parameter in the evaluation of on-orbit servicing.

Effect of volatility

The more unpredictable is the market, the more valuable is the flexibility to adapt to potential variations because of the asymmetric payoffs of the option. This is illustrated in Figure 4-15 that shows the ratio of the expected value of a flexible mission to the baseline expected value for different market volatilities. The value of the option increases as volatility increases. As the market volatility increases, the range of potential values of the uncertainty parameter X broadens. Both higher and lower values of X may be achieved. For lower values of X , no upgrade will be performed and the "option will not be exercised". For the higher values of X , the satellite is upgraded leading to higher revenues. Therefore, a higher level of uncertainty creates more opportunities the space operator can benefit from. The value of the option to upgrade therefore increases.

Effect of the cost and risk of a servicing operation

For a low cost of servicing and a low risk of a catastrophic failure of the servicing operation, the option to service has a significant value even for very low volatilities. The cost and risk of a servicing operation are both negatively correlated with the value of the option to service. For example, for a market volatility of 40% and a servicing risk of 1%, an increase of 100% in the servicing cost (from \$65 million to \$130 million) translates to a decrease of 8.7% in the expected value for the flexible architecture. For a market volatility of 40% and a servicing cost of \$65 million, an increase of the servicing risk from 1% to 5% translates to a drop of 6.5% in the expected value of the flexible architecture.

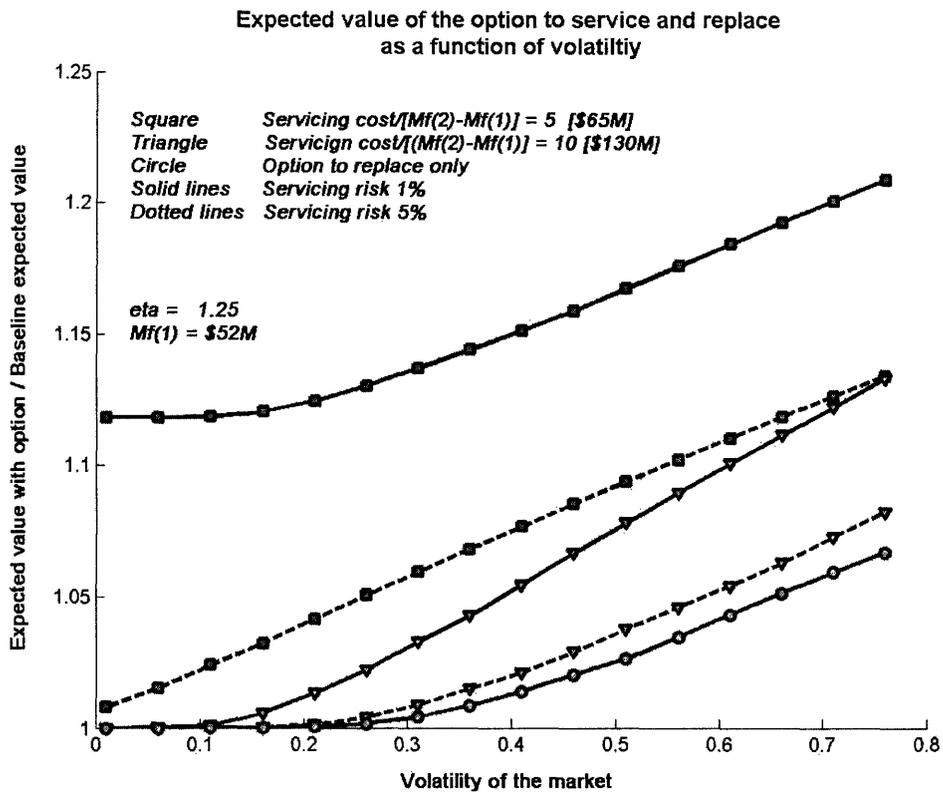


Figure 4-15: Effect of market volatility on the option value.

Optimal architecture

The conditions for which designing for serviceability is optimal compared to replacing or not upgrading the satellite are investigated in order to help space designers in making initial design choices. We first examine the optimal design choice depending on market conditions, assuming given characteristics of the servicing infrastructure. The optimal design choice depending on the characteristics of the servicing infrastructure offered is then studied, assuming given market conditions.

Figure 4-16 shows a map of the optimal architecture depending on market volatility and the effect of the upgrade η , assuming a servicing operation can be provided for \$175 million with a risk of 1%. Designing the satellite to be serviceable is optimal for higher market volatilities and if the upgrade has a larger effect on forecasted revenues. In this area, some scenarios may make servicing valuable. It must be noted that replacement is not excluded of this area, but at least for one value of X servicing is preferred to a replacement of the satellite. The fact that servicing is preferred over replacing the satellite is the effect of the responsiveness of on-orbit servicing compared to the replacement option as explained in Section 4.4.3. For higher values of η and higher volatilities, the loss of 2 years of revenues while designing and launching the new satellite is higher than the extra cost of servicing. For low values of η and low volatilities, the potential added revenues from an upgrade do not offset the cost of upgrading. The impact of servicing risk on the design choices are illustrated in Figure 4-17, which shows the same decision map as Figure 4-16 for a servicing risk of 10%. The set of conditions for which satellite upgrade is attractive is not affected by servicing risk. The level of risk of a servicing operation affects the method chosen to implement the upgrade and the relative attractiveness of on-orbit servicing and satellite replacement. If the satellite is lost during a servicing operation, no revenue is generated over the rest of the time horizon. If the replacement satellite is lost, revenues can still be generated by the operation of the initial satellite. Therefore the catastrophic failure of a servicing operation has larger consequences than a failed replacement launch. As the risk of servicing increases, the potential loss of future revenues is larger than the added cost of launching a new satellite and the loss of 2 years of added revenues. Replacement is favored over servicing and the frontier of the serviceability zone shifts to the right hand corner. A similar map can be drawn to investigate the sensitivity of the optimal architecture to the characteristics of the

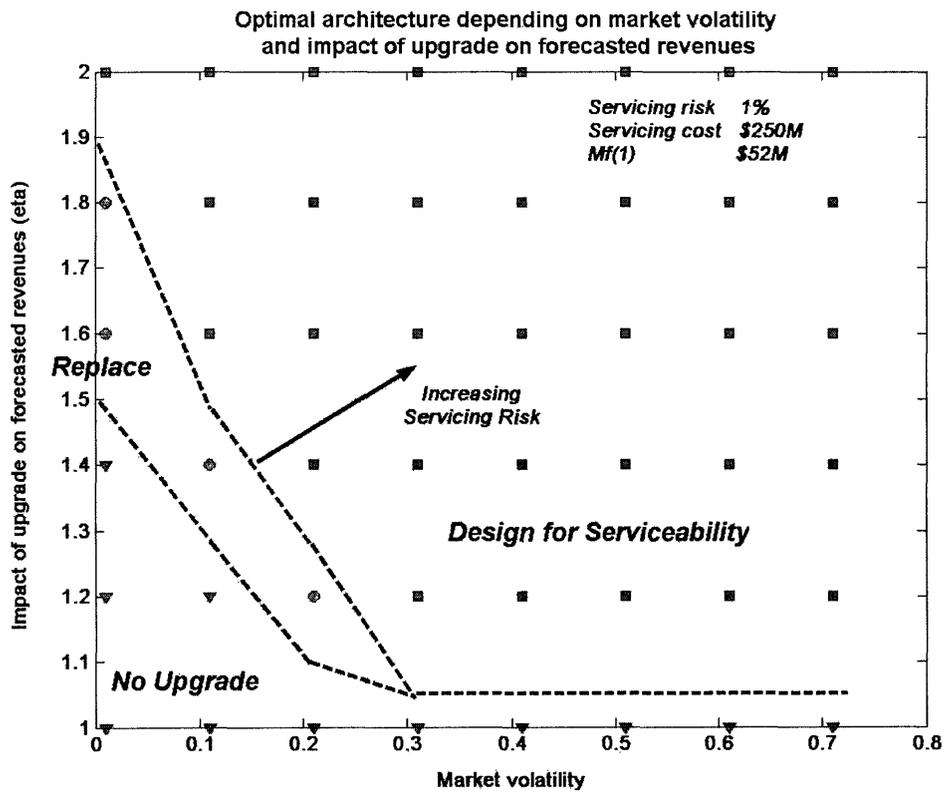


Figure 4-16: Optimal architecture depending on market volatility and the impact of the upgrade on forecasted revenues assuming a servicing risk of 1%.

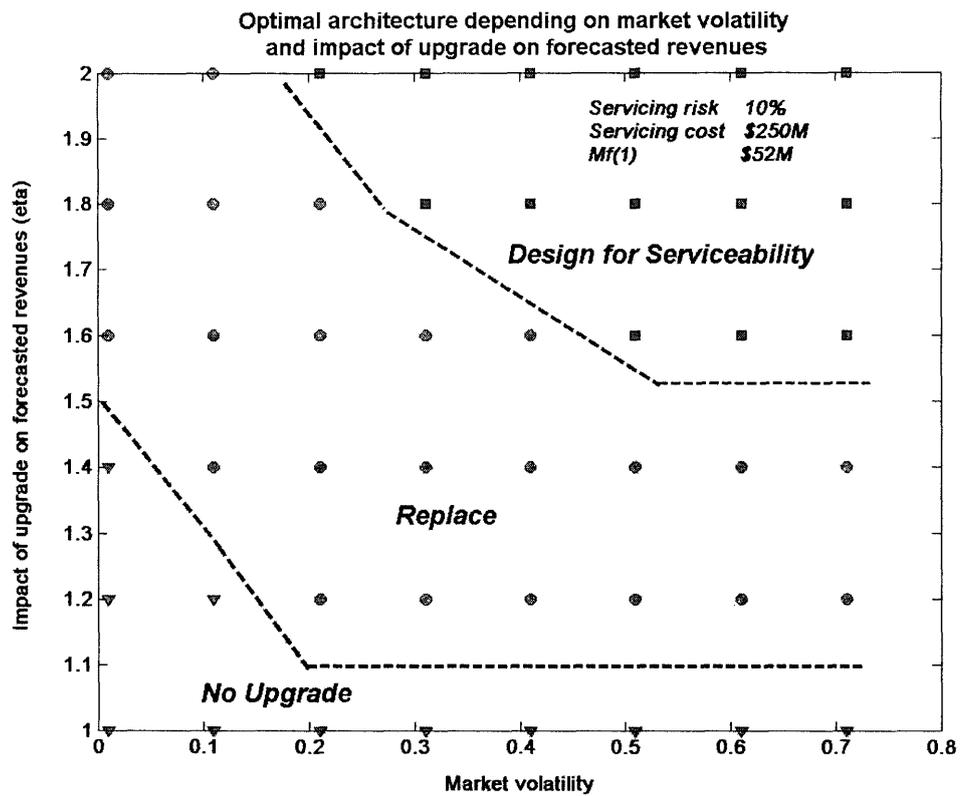


Figure 4-17: Optimal architecture depending on market volatility and the impact of the upgrade on forecasted revenues assuming a servicing risk of 10%.

servicing infrastructure, for a given set of market conditions. Figure 4-18 shows such a map for a market volatility of 40%, initial forecasted revenues of \$52 million and an increase in forecasted revenues of 25% with an upgrade. In these conditions, there are some values of X for which the satellite should be upgraded and the trade off is between servicing or replacing the satellite. As expected, designing for serviceability is more attractive for low servicing costs and risk levels. The frontier shows the maximum servicing risk for which a demand for servicing still exists depending on the cost of a servicing operation. If the servicing risk is above 16%, the satellite is never serviced and on-orbit servicing is not a valid concept in the given conditions. At low servicing costs, the maximum tolerable servicing risk decreases rapidly as the servicing cost increases. At high levels of servicing risk, the relative advantage of designing for serviceability compared to replacing the satellite is small. A small increase in the servicing cost is sufficient to reverse the optimal option: a small increase in cost has a large effect on the choice of on-orbit servicing. This map can be useful to the customer to determine if designing for serviceability is the preferred option but also to the provider of the servicing operation to examine the impact of servicing infrastructure design choices on the demand for on-orbit servicing.

4.4.4 Limitations of the model

There are three main limitations to this model. First, the impact of serviceability on the cost of the initial satellite has not been explored in this model and will be an important factor to investigate. Second, it is assumed that there is no limitation on the level of revenues the satellite can generate, implicitly assuming that any level of demand can be satisfied by the satellite. The capacity limitation of the commercial satellite has to be taken into account for more realistic results. Finally, the effect of the upgrade on the satellite is key and should be refined. A more technical model of the upgrade and how it affects the initial satellite is needed in order to get a better estimation of the impact on revenues, on the cost of the initial satellite and on the development cost of the upgrade.

4.4.5 Conclusions

Some first insights can be derived from this simple example of a commercial mission facing uncertain revenues. The use of a dynamic valuation process is key to take into account managerial flexibility. The space operator makes a decision based on the state of

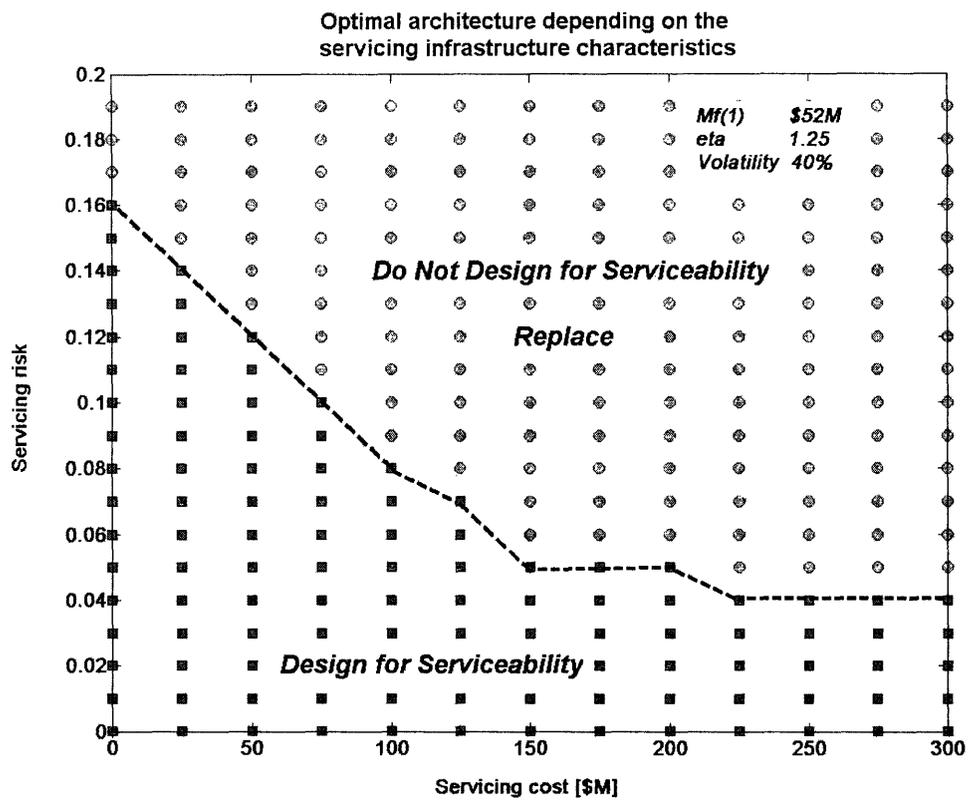


Figure 4-18: Optimal architecture depending on the servicing infrastructure characteristics.

the market observed at the time of decision. The flexibility value can account for a large part of the total expected value of the mission and therefore should not be overlooked. The value of upgrading depends heavily on the effect of the upgrade on the revenue stream. A more detailed technical model of the impact of the upgrade on the system and on the revenues is necessary to derive more applicable results. The cost of servicing as well as the risk of a servicing operation are determinant in the use of on-orbit servicing. To be competitive with the replacement option, the cost and risk of servicing must be low. The relative responsiveness between a new launch and a servicing operation is also key in the choice of on-orbit servicing over the replacement of the satellite.

Major parameters are not taken into account in this simple model and a more in depth study must be done to derive more precise insights on the value of on-orbit servicing. The effect of the upgrade on the revenues and on the system, the limitation of the revenues generated by the upgrade and the impact of designing for serviceability must be taken into account. In the next chapter, a more detailed example will be presented considering a power system upgrade on a GEO communication satellite. This more refined model attempts to take into account in some extent the limitations identified in this model.

Chapter 5

A commercial GEO communication satellite facing uncertain demand

Power output is a key parameter in communication satellites that drives capacity. Current communication satellites commonly generate 10kW power at beginning of life. Solar panels need to be oversized at beginning of life to compensate for solar cell degradation and meet the customer power requirements at end of life. The upgrade or repair of solar panels is a potential application for on-orbit servicing. The example of the upgrade of solar panels on a GEO communication satellite facing an uncertain demand is explored. The upgrade is assumed to restore the beginning of life power by adding new sections to or by replacing sections of the solar panels.

In a first approach, power upgrade is considered as a way to increase the satellite capacity for a given power level at beginning of life. In a second approach, the trade off between upgrading the solar panels and designing for a higher BOL power output is investigated. Different architectures are compared by varying the degree of flexibility, the solar cell type chosen in the design and the design lifetime of the spacecraft.

5.1 Presentation and objectives

5.1.1 Impact of the servicing operation

By regularly servicing the satellite to restore beginning of life power, the capacity of the communication satellite can be increased. This can be illustrated by considering two

satellites designed for the same lifetime, the same beginning of life power and using the same solar cell type. One is a baseline satellite that cannot be serviced. The power on-board is therefore decreasing linearly with time from beginning of life (BOL) power to end of life (EOL) power. The rate of decline depends on the solar cell type used. The second satellite is a flexible architecture that is regularly serviced: in between two upgrade missions, the power generated declines linearly and the power is regularly restored to BOL level at each servicing mission. The evolution of the power output for each satellite is shown in Figure 5-1. For communication satellites not bandwidth limited, the capacity of the satellite is directly related to the power available. The payload is assumed to be sized so as to offer a constant capacity over the satellite lifetime. The payload is therefore designed for the lowest power level available on-board. Because of the regular power upgrades, the minimum power level on the serviceable satellite is higher than for the baseline satellite leading to an increase in capacity for the serviceable architecture.

The first approach adopted is to compare different architectures with the same initial BOL power to estimate the value of the added capacity offered by serviceable satellites. In a second approach, solar panels upgrade is considered as an alternative to oversizing solar panels. The cost of designing for a higher BOL power is traded against the cost of servicing to determine the optimal design choice.

An upgrade mission may not be limited to restoring BOL power and could be used to increase the power output above the initial level. An increase in the power generated by the solar panels would have consequences on other subsystems. In particular, the thermal subsystem must be adequate to manage the corresponding additional heat. The thermal subsystem could either be upgraded at the same time as the solar panels or be oversized in the initial design to offer the opportunity to increase the power level once the satellite is in orbit. Moreover, in the case of a communication satellite, the increase in power must be accompanied by the installation of additional transponders in order to increase the satellite capacity. In this model, only the solar panels are assumed to be serviceable. The constraints imposed by other subsystems, such as the thermal subsystem, the batteries and the payload, are taken into account by only allowing the power level to be restored to BOL level and not increased. It is assumed that the degradation of those key subsystems over time is small enough to allow BOL power to be supported by the satellite through its lifetime.

The upgrade of solar panels can be technically done by different means. One option is

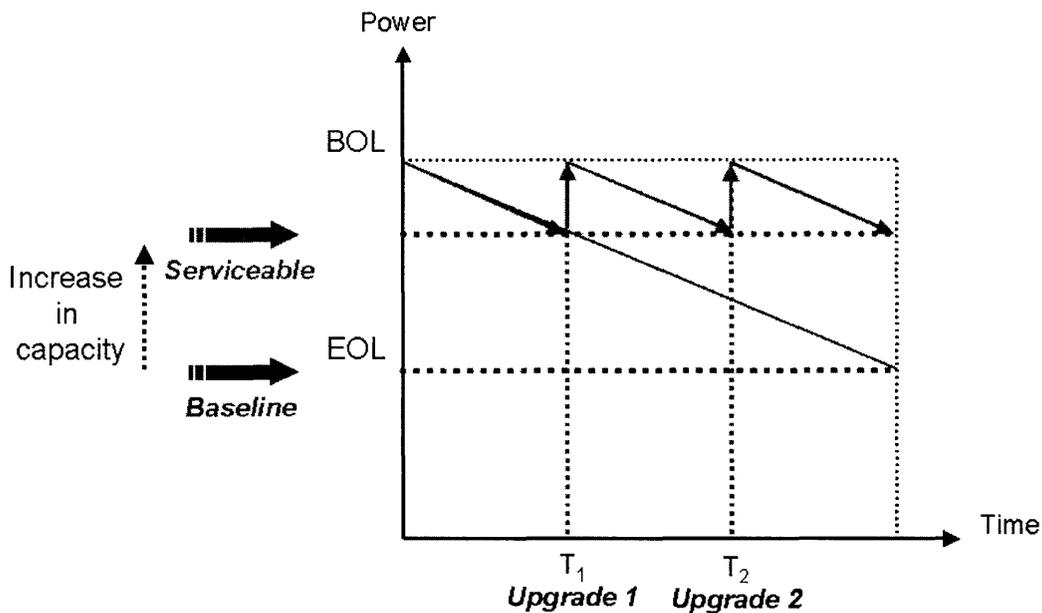


Figure 5-1: Impact of solar panel upgrade on satellite capacity.

for the servicer to attach additional solar cell panel sections to the initial satellite solar panels. Another more complex technique is to replace sections of the solar panels with non degraded solar cells. The mass distribution and geometry of the satellite may be altered by this operation, which may impact the attitude control of the satellite. It is considered that the modifications can be implemented so that the attitude control subsystem does not need to be modified to control the upgraded satellite.

5.1.2 Model characteristics

Three features have been incorporated in an attempt to take into account the limitations identified in the model of a commercial mission facing uncertain revenues:

- The impact of designing for serviceability is taken into account by assuming an initial cost penalty for a serviceable satellite.
- The revenues potentially generated by the satellite are not unlimited and are constrained by the satellite capacity.
- The example of restoring BOL power on a communication satellite is simple enough to be able to get a technical estimate of the impact of the upgrade. The satellite

capacity, defined as the number of billable minutes that can be offered, is estimated as a function of the on-board power available.

In addition, multiple decision points are considered in the model.

5.1.3 Objectives

This example provides a more detailed case in which the impact of the upgrade on the mission can be estimated with more fidelity. The following issues are investigated:

- What is the value of using on-orbit servicing to upgrade the solar panels on-board a GEO communication satellite?
- What is the optimal design choice depending on the conditions the space operator is facing?
- What is the impact of a limited capacity and a limited degree of flexibility?
- What would be the demand for a servicing market in the particular case studied?

5.2 Assumptions and model description

5.2.1 Architectures compared

Satellite servicing must be compared to other alternatives in order to get an estimate of the attractiveness of on-orbit servicing. The main parameters influencing the value of the architecture are the lifetime of the satellite, the payload capacity, the type of solar cells used in the solar panel design and whether the satellite is serviceable. Five architectures combining these different characteristics are compared in the model. The characteristics of the five architectures are summarized in Table 5.1.

- **Baseline 1** The baseline 1 architecture is a standard non flexible satellite designed for a lifetime T_H equal to the time horizon of the study. Silicon Si solar cells are used and the payload is designed for end of life power. Baseline 1 is representative of a common communication satellite as seen today.
- **Baseline 2** Baseline 2 is similar to the standard Baseline 1 architecture. However, high resistance InP solar cells are used that have a lower degradation coefficient than

conventional Si solar cells. This architecture is modelled to capture the trade off between the additional cost of using high resistance solar cells and the maintenance costs of regularly restoring the satellite power with servicing missions.

- **Baseline 3** Baseline 3 is similar to the standard Baseline 1 architecture, designed for a lifetime T_H and using Si solar cells. However, the payload is designed for the power output available at a time T (with $T < T_H$). T is chosen as the time of the first decision point for the serviceable satellite. The capacity of the satellite is constant until T and then decreases as the power output declines with the solar panels degradation. Baseline 3 corresponds to taking advantage of the extra power available before solar cells degrade by adding transponders that are later turned off as the power degrades. The capacity of Baseline 3 is equivalent to a satellite serviced once at T .
- **Serviceable architecture** This architecture is the only satellite that is designed to be accessed by a servicer for solar panel upgrade. The satellite is initially designed for a lifetime T_H and Si solar cells are chosen in the design. Since the satellite is designed to be serviced regularly, the payload is assumed to be sized for the power level available at the first decision point.
- **Short lifetime architecture** This satellite is designed for a lifetime shorter than T_H . At end of life, the satellite can be replaced if deemed profitable. The payload is designed for end of life power and Si solar cells are used. Cost savings can be realized by designing the satellite for a shorter lifetime. The replacement costs must be compared to the additional cost of designing for a longer lifetime and the upgrade costs. The satellite end of life is chosen to coincide with the launch of a new satellite if a replacement decision is made at the first decision point T . The satellite lifetime chosen is therefore the sum of T and the pre-launch period.

The decisions made available to the decision maker for each architecture are shown in Table 5.1. For all architectures, the mission can be replaced or abandoned if operational costs exceed revenues. Only the serviceable satellite can be serviced. Some power profiles for the five architectures are illustrated in Figure 5-2.

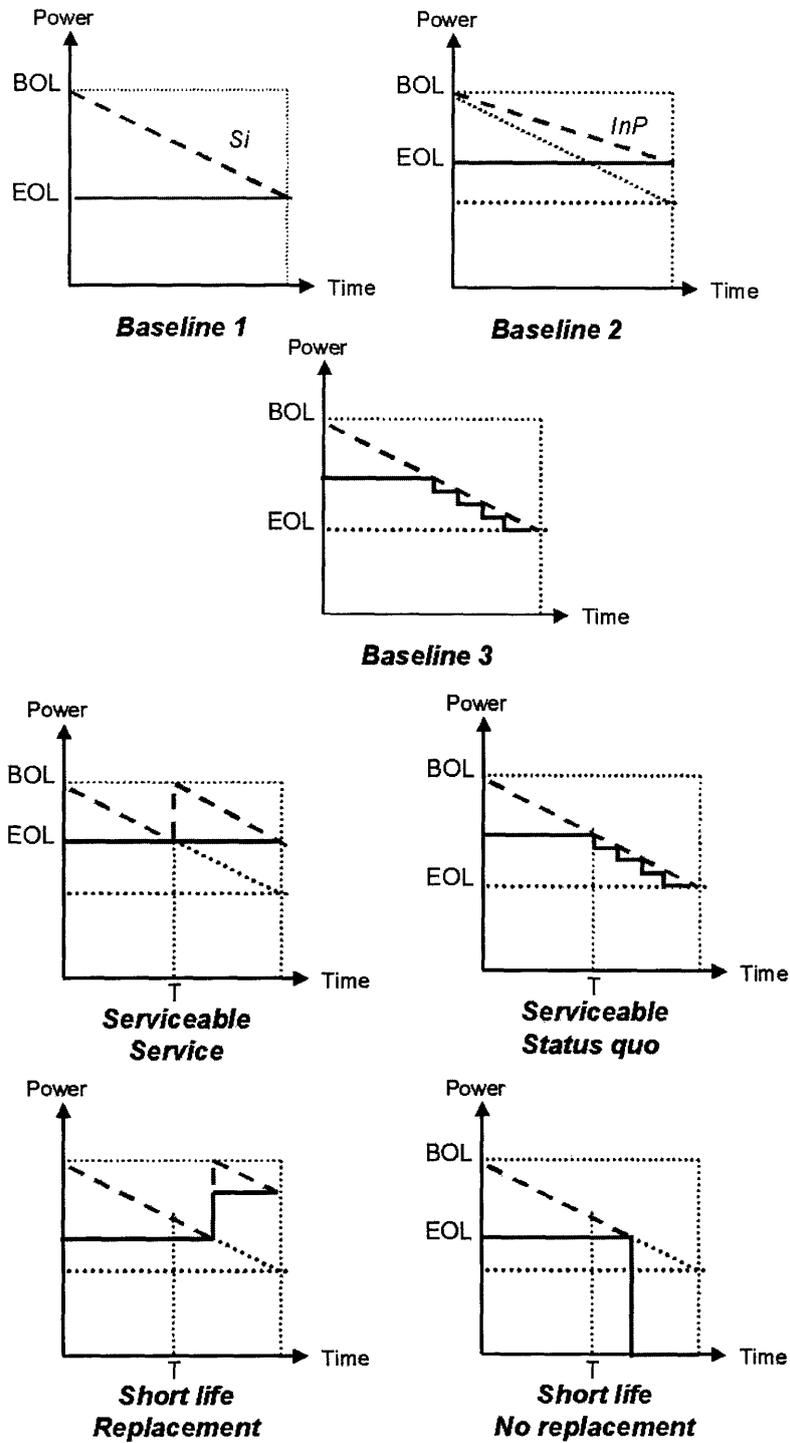


Figure 5-2: Selected power profiles for the five architectures. The dotted line represents the evolution of the power level on-board the satellite. The solid line is the power level that determines the maximum satellite capacity. T represents a single decision point.

Architecture	Baseline 1	Baseline 2	Baseline 3	Serviceable	Short Lifetime
Characteristics					
Design Lifetime	T_H	T_H	T_H	T_H	$T + \text{pre-launch}$
Solar Cell Type	Si	InP	Si	Si	Si
Time for sizing payload	EOL	EOL	T	T	$T + \text{pre-launch}$
Serviceability	No	No	No	Yes	No
Decisions available					
Status Quo	Yes	Yes	Yes	Yes	Yes
Abandon	Yes	Yes	Yes	Yes	Yes
Service	No	No	No	Yes	No
Replace	Yes	Yes	Yes	Yes	Yes

Table 5.1: Description of the five architectures compared. Both the characteristics of each architecture and the decisions available to the space operator are shown.

5.2.2 Decisions

The following assumptions are used concerning the decisions that can be made.

In case of a replacement, the new satellite has the same characteristics than the initial satellite. However, in some cases, designing the new satellite for the same lifetime as the initial vehicle may lead to a lifetime that exceeds the time horizon considered. To adopt a comparable time frame for the comparison of the architectures, the new satellite lifetime is the minimum between the initial lifetime and the time remaining until the end of the time horizon. In any case, the payload is designed for the minimum between the time for which the initial satellite payload was designed and the satellite end of life. Therefore the replacement satellite may have a higher capacity than the initial satellite. As in the model of a commercial mission facing uncertain revenues, a pre-launch period of 2 years is assumed to design, test, produce and launch the new satellite. If a replacement satellite is being designed, it is assumed that the decision maker will not decide to replace the system before the currently designed satellite is launched.

The decision to abandon is considered irrevocable and the satellite is no longer operated until the end of the time horizon. No revenues are generated and no operational costs are incurred. If a new satellite was being designed to be launched at a later period, the design and production of the new satellite is also abandoned.

The servicing operation is assumed to be conducted immediately and affects revenues and costs in the same period the decision to service is made. A probability of failure is associated

with the decision to service. The assumptions on risk are explained in Section 5.2.8.

5.2.3 Uncertainty parameter X

In this model, market forecasts are done to predict the level of demand expected over the period of operation of the satellite. The forecasted demand level is noted \mathcal{D}_f . The actual demand the satellite faces, noted \mathcal{D} , is uncertain and may be above or below the forecasted demand. The uncertainty parameter is chosen as the ratio of the actual demand to the forecasted demand:

$$X = \frac{\mathcal{D}}{\mathcal{D}_f} \quad (5.1)$$

Demand is expressed in billable minutes per year. The uncertainty is linked to external factors and is independent of the decisions made by the space operators. X is further assumed to follow a Geometric Brownian Motion with drift α and volatility σ . The forecasted demand is assumed to be constant: $\mathcal{D}_f = \mathcal{D}_0$.

The price of a billable minute, which will be used to derive revenues, is another component of market uncertainty and is likely to evolve through the satellite operation time. However, in a desire to keep the model simple and consider a single source of uncertainty, the price of a billable minute is considered constant through the time horizon considered. The market uncertainty is only considered through the evolution of demand.

5.2.4 Revenues

The number of billable minutes sold is the minimum between the actual demand \mathcal{D} and the maximum satellite capacity N . The actual revenues are derived as the product of the number of billable minutes sold and the price of a billable minute $P_{\mathfrak{S}}$:

$$\mathcal{R}_{[T_k, T_{k+1}]}^m(x_k) = \int_{T_k}^{T_{k+1}} \min(N(t), \mathcal{D}(t)) P_{\mathfrak{S}} e^{-r(t-T_k)} dt \quad (5.2)$$

$$= \int_{T_k}^{T_{k+1}} \min(N(t), X(t)\mathcal{D}_f) P_{\mathfrak{S}} e^{-r(t-T_k)} dt \quad (5.3)$$

The notations used are the same as in Chapter 4.

As a first approximation for small periods, the demand and maximum capacity over a period in the binomial tree is considered constant. Since the price of a billable minute is

also assumed to be constant, we can calculate the revenues as:

$$\mathcal{R}_{[T_k, T_{k+1}]}^m(x_k) = \min(N(t), x_k \mathcal{D}_f) P_{\$} \int_{T_k}^{T_{k+1}} e^{-r(t-T_k)} dt \quad (5.4)$$

A 40% corporate tax is included in the model.

5.2.5 Capacity calculation

The maximum satellite capacity, defined as the number of billable minutes that a satellite can offer, is calculated from the bandwidth and the on-board power available at the time using the model developed by Chang and De Weck [6]. Chang and De Weck developed a simulation of LEO communication satellite constellations that evaluates capacity and cost depending on the constellation characteristics. Various configurations were evaluated and the model was benchmarked against Iridium, Globalstar and Teledesic data. The model has been adapted to the case of GEO communication satellites. A MF-CDMA multiple access technique with a Viterbi modulation code and QPSK phasing were used.

Power available for the payload It is assumed that 40% of the satellite power is allocated to the satellite bus and only 60% can be used by the payload [37]. During the initial period prior to the time for which the payload is sized, the capacity is constant and calculated using the power level available at the time t_{pay} for which the payload is sized.

$$P_{pay} = 0.6 P_{BOL} (1 - L_d)^{t_{pay}} \quad (5.5)$$

where P_{pay} is the power used to calculate the satellite capacity in the initial period, P_{BOL} the BOL power level, L_d the solar cell degradation coefficient and t_{pay} the time for which the payload is sized.

After t_{pay} , the power available for the payload at time t depends on the decision made and the architecture considered. Some power profiles for the calculation of the satellite capacity are shown in Figure 5-2.

Number of billable minutes The power available for the payload is used as an input in the simulation that outputs the number of simultaneous users the satellite can handle.

The number of billable minutes is then calculated as:

$$N(t) = N_{user}(t) * (365 * 24 * 60) \quad (5.6)$$

where $N(t)$ is the capacity of the satellite at time t and $N_{user}(t)$ corresponds to the number of simultaneous users a satellite can handle at time t as outputted by the simulation.

The capacity of the system when entering the decision point is key to the evaluation of the revenues. In the backward process adopted in the evaluation, the entry capacity needs to be captured in the set of entry states. The choice of the system entry states is explained in more details in Section 5.2.9.

5.2.6 Initial operating capability cost

The cost of the satellite depends on the architecture selected. Three major parameters drive satellite cost: the satellite design lifetime, the power at BOL and whether the satellite is designed for serviceability. The cost relations are adapted from Saleh [32] and SMAD [37]. The mass of each subsystem is first derived for a non serviceable satellite as a function of the design lifetime and the BOL power output. The BOL power level mainly impacts the size of the batteries, the surface of the solar panels and the mass of the power distribution unit. The design lifetime mainly impacts the size of the battery because of the decline of the Depth of Discharge (DOD), the propulsion system for attitude control and the telemetry, tracking and control subsystem because of the added redundancy required to maintain high reliability. The mass of the payload is proportional to the number of transponders required to provide the satellite capacity. Each transponder is assumed to weigh 27.5kg as used by Mc Vey [22]. The cost of the satellite is estimated from the satellite dry mass using a Cost Estimating Relation [37].

Adapting satellite cost for solar cell type The cost of the solar panels must be modified depending on the type of solar cells used. The specific performance of the solar cells used drives the solar panel surface and mass required for a given power output. InP solar cells have a lower degradation coefficient but InP solar panels are more expensive to develop. First the surface area of the solar panels required to provide a given BOL power output is estimated from the specific performance of the solar cells used. A specific

performance of 30W/kg (respectively 36W/kg) has been chosen for Si (respectively InP) solar cells. The cost of Si solar panels has been estimated at \$100,000/m² from satellite data. InP solar panels are assumed to cost three times more than Si solar panels.

Adapting satellite cost for serviceability In order to be serviced, the satellite must be designed for serviceability. First a docking system is assumed to be installed to allow the servicer to attach to the target satellite. A mass of 32kg is assumed for the docking system as used by Mc Vey [22]. In addition, the satellite must be designed to be upgraded: the servicer must be able to attach new sections or replace sections of the solar panels. A mass penalty of 10% of the satellite dry mass [13] is considered in this work to account for the cost of designing for serviceability. This assumption is believed to be conservative in this case since only the solar panels may need to be redesigned.

5.2.7 Other costs

Other costs include the initial launch costs, the costs incurred by a decision and operational costs. The costs are taken into account at the point in time when they are incurred. In particular, since a decision to replace translates to expenses over the following two years, part of the costs incurred by the decision to replace are impacted at later decision points.

Launch costs The launch costs are assumed to be the same for all architectures and estimated at \$97.5 million per launch. The costs are spread evenly over a pre-launch period of 2 years. The assumptions on launch failure rate and launch insurance costs are the same as for the model of a commercial mission facing uncertain revenues presented in Section 4.4.2.

Replacement costs When a satellite is replaced, the costs incurred include the cost to design and produce the new satellite, the launch costs and the insurance costs. Because the new satellite may differ slightly from the initial satellite and have a lower design lifetime, the cost of the new satellite is recalculated.

Servicing costs The costs incurred by a servicing operation include the price of the servicing mission, the cost of the upgrade unit and insurance costs. The cost of the upgrade unit is taken as the cost of the section of solar panel necessary to restore BOL power. The

power to be delivered by the added section is the difference between BOL power and the current degraded power level and calculated as explained in Section 5.2.6. The amount insured is based on the depreciated value of the satellite and the loss of revenues in case of a failure calculated on the basis of the capacity of the satellite at end of life. The space operator is therefore assumed to insure the potential constant revenues the satellite could generate over the remaining time of operation.

Abandon costs No termination costs are considered and no costs are incurred if the mission is abandoned.

Operation costs Operation costs are assumed to be identical for all architectures and independent of the satellite capacity. A cost of \$10 million per year is chosen.

5.2.8 Launch or servicing failure

If a failure occurs during a new launch or a servicing operation, the space operator can still decide to pursue the mission. The failure of the replacement launch does not affect the initial satellite that is assumed to be still operational. If the initial satellite is lost during a servicing mission, a new satellite may be launched at a later decision point if the market conditions are favorable. Therefore two calculations must be done at each point in the binomial tree and for each entry state: one if the operation is successful and one if the operation is not successful. This is equivalent to considering a second source of uncertainty, corresponding to the operation success, combined with market uncertainty in the decision tree. The calculation for a successful operation is similar to what has been described previously. In case of a failure of the operation at T_k :

- If a replacement launch fails, the revenues generated over the period $[T_k, T_{k+1}]$ are those generated by the initial satellite. The system enters the next decision point in the same state m that if no replacement satellite had been launched. The expected value of the mission over the period $[T_{k+1}, T_H]$ can be found from m . In addition, an insurance payment is received equal to the amount insured, which is based on the value of the lost satellite.
- If a servicing operation fails, the initial satellite is assumed to be lost. No revenues are generated over the period $[T_k, T_{k+1}]$. No operational costs are incurred during the

period. The system enters the next decision point in a failed state. The expected value of the mission over the period $[T_{k+1}, T_H]$ for a system entering T_{k+1} in a failed state will have been calculated in the previous steps of the backwards process. In addition, an insurance payment is received at T_k equal to the amount insured, which is based on the depreciated value of the lost satellite and the loss of revenues.

At each point in the binomial tree and for each entry state n , two end states are derived corresponding to the optimal end state if the operation is successful and a failed state if the operation is not successful. The expected value at the point x_k considered in the binomial tree and for the entry state n is given by:

$$EV_{[T_k, T_H]}^{n \rightarrow m}(x_k) = P_f^d \left(EV_{[T_k, T_{k+1}]}^{n \rightarrow m_f}(x_k) + EV_{[T_{k+1}, T_H]}^{m_f}(x_k) \right) \quad (5.7)$$

$$+ (1 - P_f^d) \left(EV_{[T_k, T_{k+1}]}^{n \rightarrow m}(x_k) + EV_{[T_{k+1}, T_H]}^m(x_k) \right) \quad (5.8)$$

where d represents the operation considered (either a replacement or a servicing operation), P_f^d the probability of failure of the operation d and m_f represents the failed state.

5.2.9 Entry states

Time delays

All decisions have a direct impact on revenues and costs except for the replacement option. The pre-launch period assumption implies that the decision to replace has consequences over the two years following the time at which the decision is made. If the time between two decision points is smaller than 2 years, the calculation at a decision point will depend on whether the decision to replace has been made at the previous decision point. The time delay for a replacement means that the new satellite is launched at a different decision point from the one at which the decision to replace is made. Costs are incurred at all decision points until the replacement satellite is launched and revenues are impacted at the decision point at which the replacement satellite is launched independently from the decision made at those intermediary decision points. Therefore, the consequences of a replacement decision must be captured in the system entry states to decouple the calculation at a decision point from previous decisions.

Entry states

Two characteristics are necessary to carry the calculation at a decision point independently from the path prior to the decision point: the capacity of the system when entering the decision point and the situation regarding a potential replacement launch. A system entry state is defined as the combination of an entry capacity and a replacement status. All potential capacity levels that may be reached depending on prior decisions are listed in the entry states. The replacement status indicates whether a replacement satellite is being designed and the time remaining until the launch of the replacement satellite. To limit the number of entry states to a reasonable size, the set of tested entry states is sorted for each time period eliminating some invalid states.

5.3 Results

The general assumptions chosen for the results presented are summarized in Table 5.2. First the impact of the assumption of a limited satellite capacity on the value of the option to service is investigated. The impact of market conditions on the optimal architecture to implement is then studied to determine the conditions for which a serviceable satellite is the preferred option. The demand for the servicing market is evaluated depending on the characteristics of the servicing infrastructure. Finally, a different approach to the problem is adopted by considering the strategy of designing for a lower BOL power and regularly upgrading to compensate for solar cell degradation.

5.3.1 Impact of capacity limitation

The value of an option usually increases with volatility because of the asymmetric payoffs of an option. As explained in Section 4.4.3, a higher volatility translates to higher potential upsides and lower potential downsides. In the case of a put-like option that acts as an insurance, the option will protect against higher potential losses while it will not affect the revenues when market evolution is favorable. The value of the option should increase because more losses are prevented. In the case of a call-like option, the option allows taking advantage of new opportunities. In a more volatile market, higher demand levels may be seen for which the option is exercised and provides higher profits. The option does not affect the mission profits in the cases where market evolution is not favorable. The value of

Numerical Assumptions

Parameter	Value
Time horizon	14 years
Time between 2 decision points	2 years
Pre-launch operation period	2 years
Launch cost	\$97.5M
Pre-launch operation costs	\$3M
Operation costs	\$10M per year
Launch failure rate	15%
Forecast demand	\$260M
Price of a billable minute	\$ 0.2
BOL power	15kW
InP panel cost	300% of Si panel cost
Drift α	5.39%
Risk free discount rate	5.39%

Table 5.2: Numerical assumptions for the study of a commercial GEO communication mission facing an uncertain demand.

the option should be higher with a higher volatility since more opportunities are available that generate higher profits.

Abandon option

The abandon option is a put-like option that is similar to an insurance and limit losses. The value of the abandon option for Baseline 1 is shown in Figure 5-3 for an initial demand close to the capacity of the Baseline 1 satellite with a 15kW BOL power and for a single decision point 7 years after launch. The abandon option value increases with volatility until a plateau value is reached. The maximum plateau value of the option corresponds to the maximum losses that can be prevented by abandoning the mission. In the model considered, the maximum option value equals the total discounted operation costs incurred from the decision point until the end of the time horizon. The \$10 million operation cost paid every year over the 7 last years of the mission and discounted back to the time of launch amounts to \$40 million dollars. The value of the abandon option for a given volatility depends on the initial forecasted demand. The higher the initial forecasted demand is, the higher the expected revenues are. The mission is more profitable and less often abandoned. For a given volatility, the value of the abandon option decreases with increasing forecasted demand \mathcal{D}_f as illustrated in Figure 5-4.

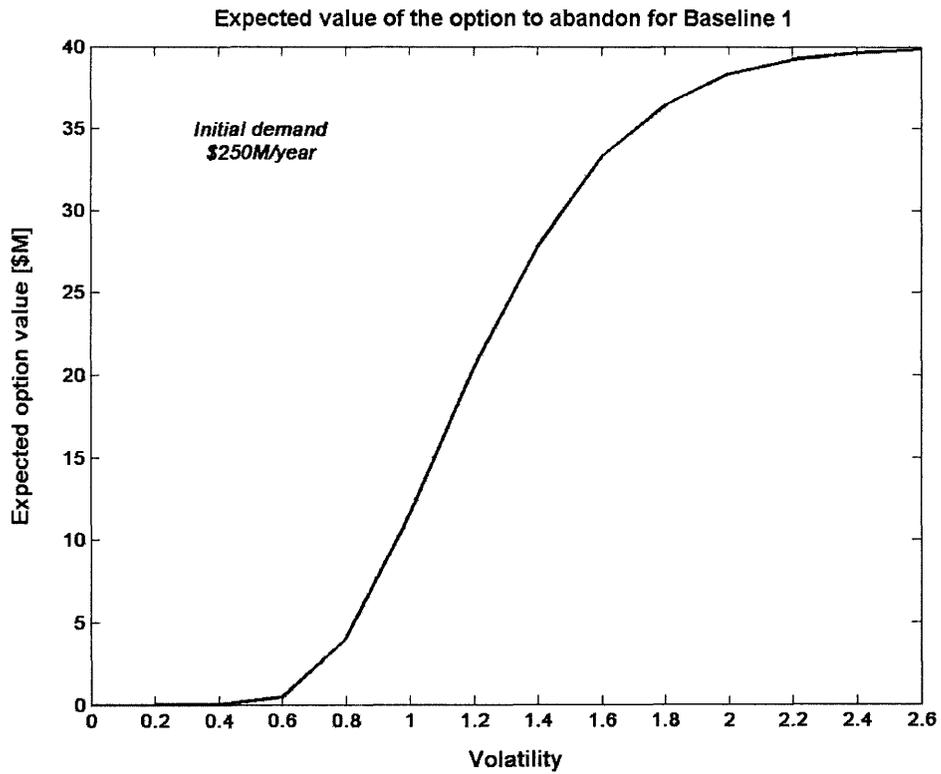


Figure 5-3: Value of the abandon option for an initial demand of \$250 million. A forecasted demand of \$250 million corresponds to the Baseline 1 satellite capacity for a power at beginning of life of 15kW.

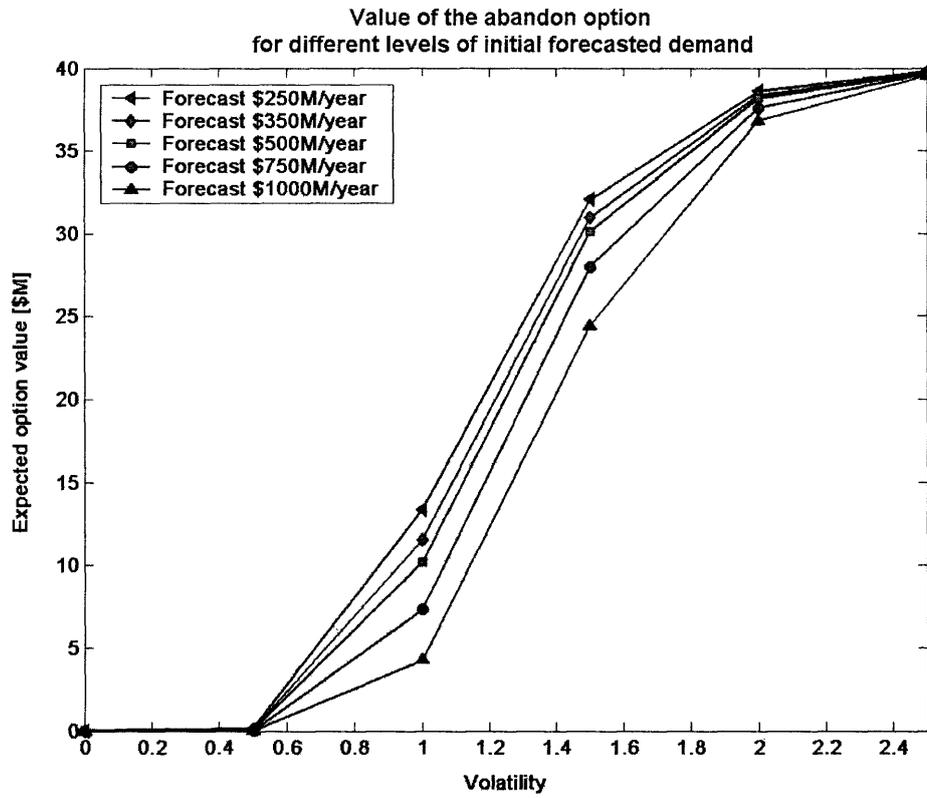


Figure 5-4: Value of the abandon option for various levels of the initial demand. A forecasted demand of \$250 million corresponds to the Baseline 1 satellite capacity for a power at beginning of life of 15kW.

Option to service

The value of the option to service is estimated against the expected value of the Baseline 1 architecture. The option to service is a call-like option and its value would be expected to increase as volatility increases. However, the service option value does not seem to follow the expected pattern. Figure 5-5 illustrates the difference between the expected values for the Serviceable and the Baseline 1 missions. A single decision point model is used for this figure. In order to better illustrate the phenomenon, the impact of the upgrade on the capacity, referred to as “effect” in Figure 5-5, is artificially set. The option value first increases with volatility as expected, reaches a peak for a given volatility before decreasing as volatility further increases. This behavior is believed to be the consequence of the limitation in the satellite capacity that prevents the space operator to take advantage of very high levels of demand. Before proposing an hypothesis to explain the behavior of the value of the option to service, we first describe the impact of a limited capacity and the effect of an increase in volatility.

The option to service only has value if the demand level goes above the capacity of the Baseline 1 architecture. In this case, the additional capacity of a serviceable satellite allows to serve more users and to gain additional profits. Once the demand level is above the capacity of the Serviceable architecture, the total satellite capacity is sold and no additional profits are gained by an increase in demand. The additional value provided by a serviceable satellite is constant for all the demand levels above its maximum capacity, and equals the effect of the upgrade.

An increase in volatility has two effects in the binomial model: 1) the jump size of X at each period in the binomial tree increases, which means that the variation in demand over a period is larger and 2) the probability of a step up decreases, which means that the probability of seeing a decrease in demand over the next period is higher.

Hypothesis An hypothesis is proposed to explain the behavior of the value of the option to service as a consequence of the capacity limitation. It must be noted that a variation in the option value is a relative change in expected value between the Serviceable and the Baseline 1 architecture. If the expected values of both architectures change by the same amount, the option value is not modified.

- **Increase in the option value** An increase in volatility may drive the demand level

above the Baseline 1 capacity therefore increasing the value of the option to service as illustrated in Figure 5-6. For a volatility σ_1 , the range of demand levels can be served with the Baseline 1 satellite. For a higher volatility σ_2 , the highest demand levels cannot be served with a Baseline 1 satellite. The serviceable satellite provides additional revenues because of its higher capacity.

- **Decrease in the option value** Let's consider the case illustrated in Figure 5-7 where the high demand levels are above the Serviceable satellite capacity. An increase in volatility potentially translates to higher demand levels. However, the space operator cannot take advantage of this favorable outcome because of the limited capacity of the satellite. There is no additional revenues generated in this case. On the other hand, a higher volatility also translates to a larger step down in the binomial tree and potentially lower demand levels. The probability of a step down also increases as volatility increases. A higher volatility σ_2 may drive a demand level below the Baseline 1 capacity that would have been still above the Baseline 1 capacity for a lower volatility σ_1 . Therefore in the case illustrated in Figure 5-7 no extra revenues are generated because the space operator cannot take advantage of the upsides whereas the extra capacity of the serviceable satellite is no longer required to serve the lower demand levels. In this case, the value of the option to service decreases when the volatility increases from σ_1 to σ_2 .

The limitation in capacity can be understood as a limited degree of flexibility. The space operator can only take advantage of a limited range of opportunities created by the uncertainty of the market. The evolution of the value of the option to service in this example seems to indicate that the value of the flexibility depends on the relation between the range of flexibility and the level of uncertainty: if the uncertainty in the environment is very high compared to the possibilities of adaptation offered by the option, the value of the option will be low.

Impact of the capacity difference on the value of the option to service According to this hypothesis, the value of the option to service and the volatility at which the peak is seen directly relates to the increase in capacity offered by a serviceable satellite. A higher increase in capacity from the Baseline 1 architecture to the Serviceable architecture has two impacts on the option value as seen in Figure 5-5:

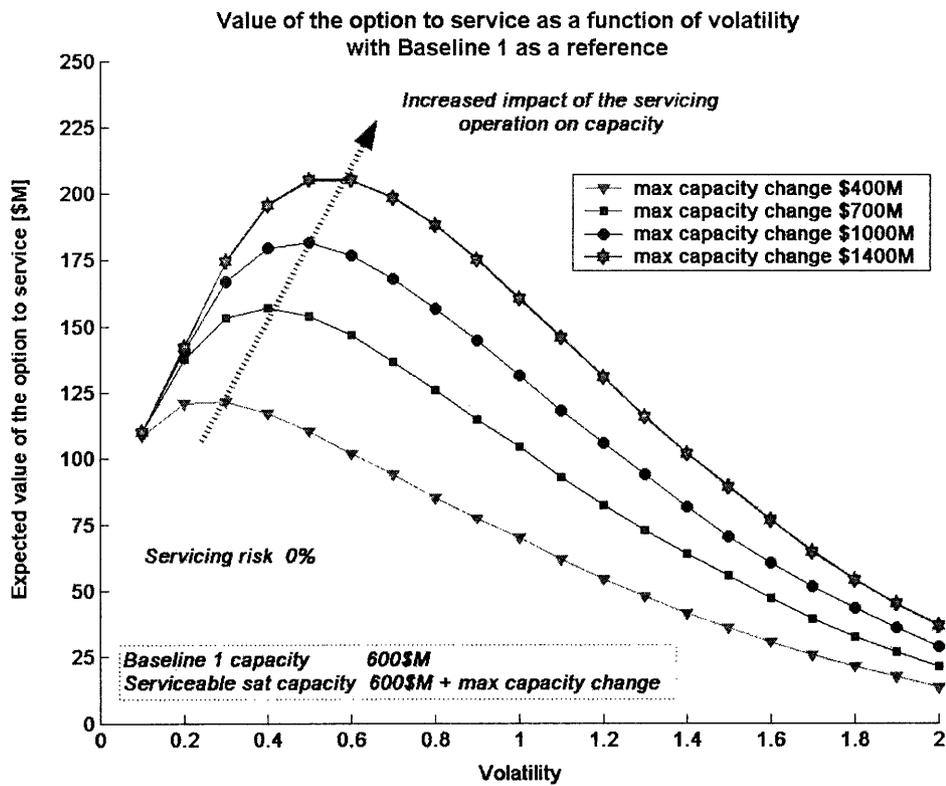


Figure 5-5: Difference in expected value between the Baseline 1 and the Serviceable architectures as a function of volatility. The calculation has been done with a single decision point.

Option value increases with volatility

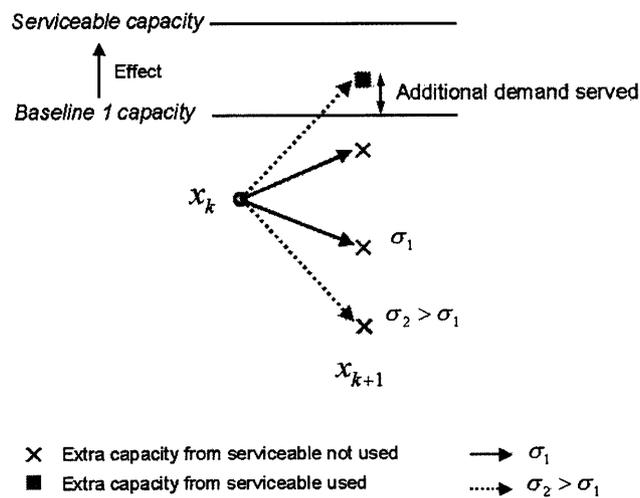


Figure 5-6: Option value increases with volatility.

Option value decreases with volatility

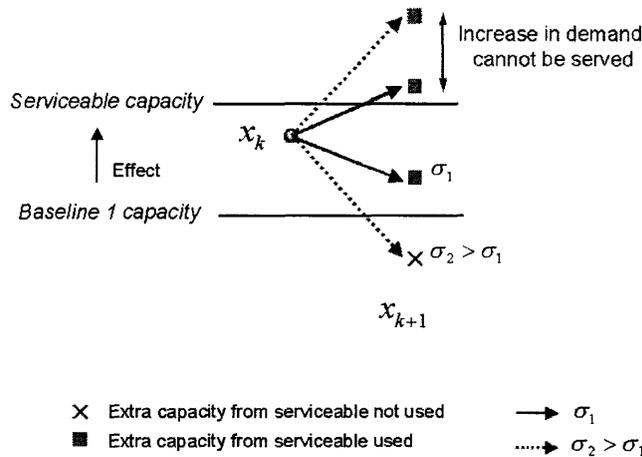


Figure 5-7: Option value decreases with volatility.

- The peak value of the option increases. A higher option value is reached when the serviceable satellite offers a higher increase in capacity because additional demand can be served.
- The volatility at which the peak is seen increases. The larger the effect on capacity is, the larger is the region of demand levels for which the serviceable satellite offers extra revenues compared to the Baseline 1 architecture and for which an increase in demand still offers an opportunity of added revenues. Therefore, a small increase in volatility that widens slightly the range of demand levels can lead to additional profits if the difference in capacity between a Baseline 1 satellite and a serviceable satellite is large enough as illustrated in Figure 5-8. An increase in volatility from σ_1 to σ_2 is considered for two effects of the upgrade on capacity, effect 1 and effect 2. For both effect 1 and effect 2, a loss in the option value is incurred when volatility increases from σ_1 to σ_2 because the lower demand level drops below the Baseline 1 capacity. However, for a larger effect on capacity, this loss can be compensated by added revenues from the upsides. The option value may therefore continue to increase for higher volatilities if the effect of the upgrade on capacity is larger. This explains why the value of the option to service peaks at a higher volatility for larger effects of the upgrade on capacity.

Impact of a larger effect on capacity

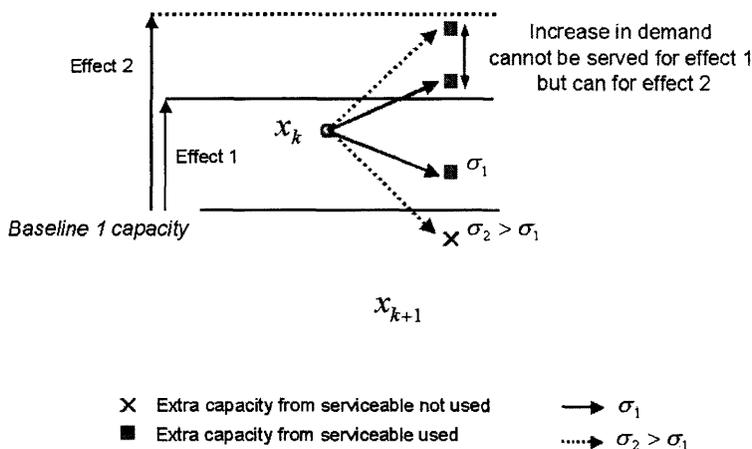


Figure 5-8: Impact of a larger increase in the satellite maximum capacity due to the upgrade.

Limitations It must be noted that the assumption of a limited capacity also increases the risk of numerical errors in the binomial model. The range of values for which the serviceable satellite offers an increase in revenues is limited and the discretization process used may not represent this range precisely enough for high volatilities. However, the potential numerical errors, estimated in comparison to a continuous distribution, seem not sufficient to change the trend described previously in the evolution of the value of the option to service with volatility.

Another limitation to be considered is the validity of the assumptions used in the model. In particular, if the capacity of the satellite serving a market is much lower than the demand observed, the space operator may launch a new satellite, new providers may enter the market and the price of a billable minute will likely increase to reflect the shortage in supply.

5.3.2 Optimal architecture depending on market conditions

Two characteristics of the market the satellite is serving are considered: the initial level of demand and the volatility of the market. A map of the optimal architecture to implement is drawn depending on D_f and σ . It can be used by space users as a tool to decide the best strategy to follow. Figure 5-9 shows such a decision map assuming that a servicing operation can be provided for a cost of \$0 and with no risk of a catastrophic failure. Using the

assumptions shown in Table 5.2, the Baseline 1 satellite offers a capacity of approximately \$260 million. Two architectures appear in the map: the Baseline 1 and the Serviceable architectures. Market volatility for communication satellites has been estimated at approximately 3% from data on past prices of transponder leases [1].

The Baseline 1 architecture appears optimal for low initial demand levels whereas the Serviceable satellite is optimal for high initial levels of demand. If the initial demand observed is low, the capacity of the Baseline 1 satellite will be sufficient to cover most of the actual demand. As the initial demand increases, the chances that the actual demand will be above the Baseline 1 capacity increase. The additional revenues that can be generated with the Serviceable satellite offset the additional cost of this architecture and the Serviceable architecture is the optimal strategy. In some cases where the initial demand level is below the Baseline 1 capacity, the Serviceable satellite should still be implemented to have the opportunity to take advantage of potential increases in demand. Because a positive drift is assumed, the mean demand increases and the added capacity of a Serviceable satellite is valuable.

It can be noted that the attractiveness of the Serviceable satellite decreases at high volatilities corresponding to the decrease in the value of the option to service discussed in the previous section. Let's consider for example an initial demand level of \$250 million. The Serviceable satellite is preferred until the volatility reaches 50% where the Baseline 1 satellite becomes the optimal strategy.

The Serviceable architecture becomes more promising as the difference in capacity between the Baseline 1 and the Serviceable satellites increases. This results from the increase in the value of the option to service with the upgrade effect as discussed in the previous section.

5.3.3 Effect of servicing risk on the optimal architecture

For a risk of servicing of 5%, the region where the Serviceable architecture is optimal is significantly reduced and two additional architectures appear in the decision map as illustrated in Figure 5-10.

The region where Baseline 1 is the preferred choice is similar for servicing risks of 0% and 5%. Baseline 1 is more promising for low levels of initial demand and high volatilities.

The region where the Serviceable satellite is optimal with a servicing risk of 0% is now separated between three architectures: the Serviceable architecture, the Baseline 2 architecture

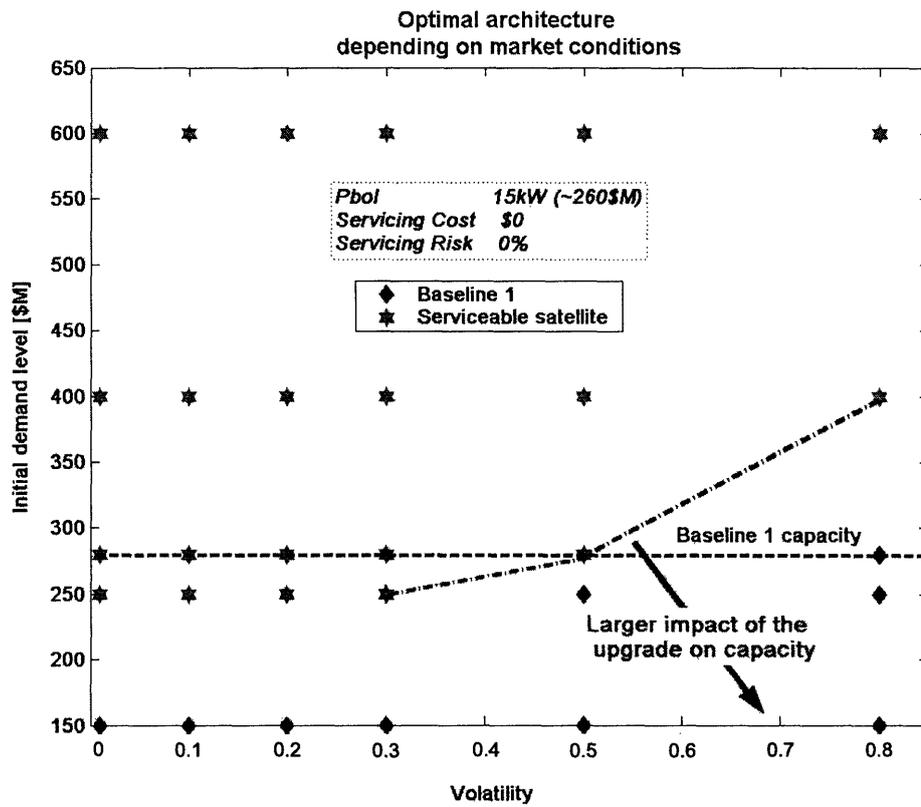


Figure 5-9: Optimal architecture depending on market conditions (initial market level and volatility) with no servicing risk. (This is the best case scenario).

that uses InP solar cells and the Baseline 3 architecture for which the payload is sized for a higher power level. It must be noted that all three architectures provide a higher capacity than the Baseline 1 satellite. The region where the space operator seeks an architecture with a higher capacity than the Baseline 1 satellite is almost similar independently from the servicing risk. However, the servicing risk impacts the method chosen to reach an increased capacity.

A comparison on the basis of capacity is necessary to understand the attractiveness of each architecture. Baseline 3 offers the same capacity as the Serviceable satellite until the first decision point is reached. The capacity of Baseline 3 then decreases whereas a serviceable satellite can be upgraded to keep the capacity at its original level. The constant capacity obtained with Baseline 2 is lower than the initial capacity offered by Baseline 3 and the Serviceable satellite. However, the Baseline 3 capacity eventually decreases below the Baseline 2 capacity level.

- The region where the Serviceable architecture is optimal is significantly reduced and designing for serviceability is only chosen for high initial levels of demand and for low market volatilities.
- For high initial levels of demand and high volatilities, designing the payload for a higher level of power and letting the capacity decline as power degrades is preferred to servicing the solar panels. Since the initial level of demand is high and the future very uncertain, the space operator's priority is to seek a high capacity in the first years of operation to secure additional profits by serving the high demand levels that are very probable in the first years of the mission (since uncertainty increases with time). Both the Baseline 3 and the Serviceable architectures offer the highest initial capacity. The advantage of the Serviceable satellite compared to the Baseline 3 satellite is to offer a higher capacity later in the mission. Let's compare the case of a low market volatility (for which a Serviceable satellite is preferred) and a high market volatility (for which Baseline 3 is preferred). A higher market volatility widens the range of potential demand levels. High levels of demand cannot be served because of the capacity limitation so that for the space operator, a higher market volatility translates to an increased risk of having lower demand levels. At high market volatilities, the additional profits generated later in the mission with the extra capacity provided by

the upgrade are not sufficient to offset the potential loss of the mission in case of a servicing failure. Therefore Baseline 3 is preferred.

- For low initial levels of demand and low volatilities, designing the solar panels with highly resistant solar cells is preferred to regularly upgrading the solar panels. In the market conditions considered, the satellite capacity available later in the mission is more important than the capacity initially available. The initial demand level and the volatility are low so that the Baseline 2 capacity is sufficient to serve the demand seen in the beginning of the mission. The extra capacity offered by the Serviceable and the Baseline 3 architectures is not necessary for the first years of the mission. Because of the drift α , the mean demand level increases with time and the volatility is low so that the spread around the mean is small. Therefore, later in the mission, an extra capacity can be valuable. Therefore Baseline 3 is less appealing than Baseline 2 since it offers a higher capacity early in the mission and a lower capacity later in the mission. The Serviceable architecture is discarded because the additional profit that can be made with the extra capacity offered by the upgrade does not offset the risk of losing the mission when upgrading to keep a high capacity.

Designing the satellite for a shorter lifetime and regularly replacing the satellite is never optimal because it is far more costly than the other alternatives. The potential cost savings from designing for a shorter lifetime are small in this model because all the satellites are assumed to be designed for the same BOL power. As the satellite lifetime is reduced, the BOL power required to generate the same EOL power decreases since the period over which the solar panels degrade is shorter. The mass of the power subsystem can be reduced and the satellite cost decreases. However, in the model considered, the same BOL power is generated and the power subsystem is similar independently from the design lifetime. Cost savings can still be realized with a shorter lifetime, in particular because a lower redundancy level is required, but they are marginal compared to the replacement costs.

5.3.4 Demand for the servicing market

In the previous sections, the optimal architecture to implement depending on market conditions has been determined. From the point of view of a potential provider, it can be interesting to determine what the corresponding expected number of servicing operations

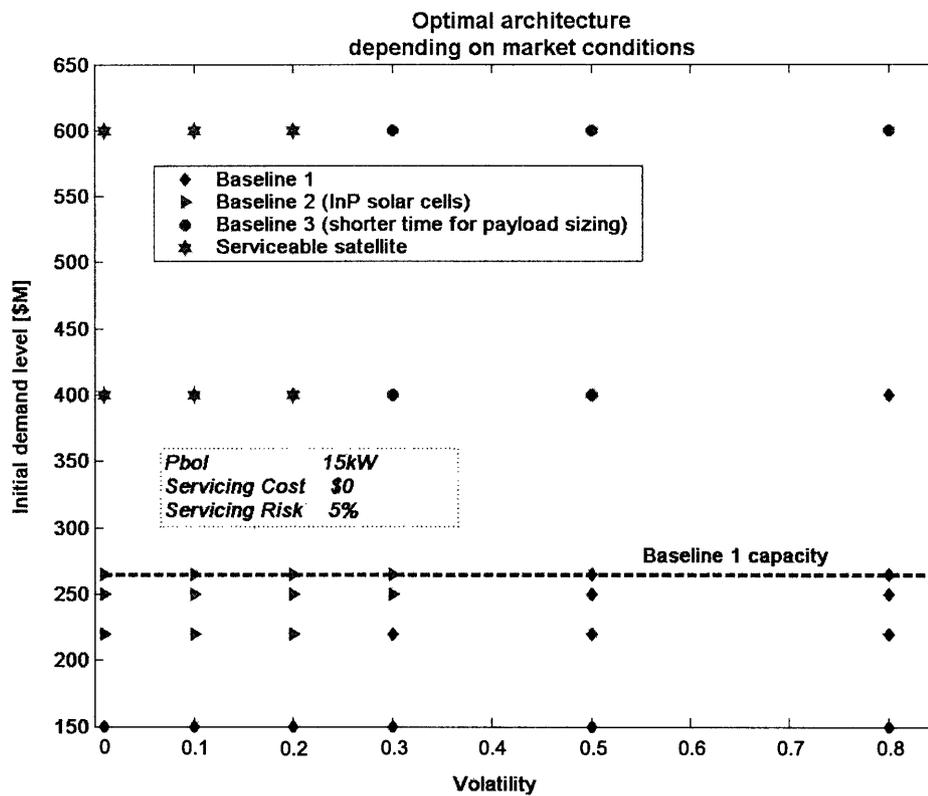


Figure 5-10: Optimal architecture depending on market conditions (initial market level and volatility) with a 5% risk of a servicing failure. The dotted line corresponds to the capacity of the Baseline 1 satellite.

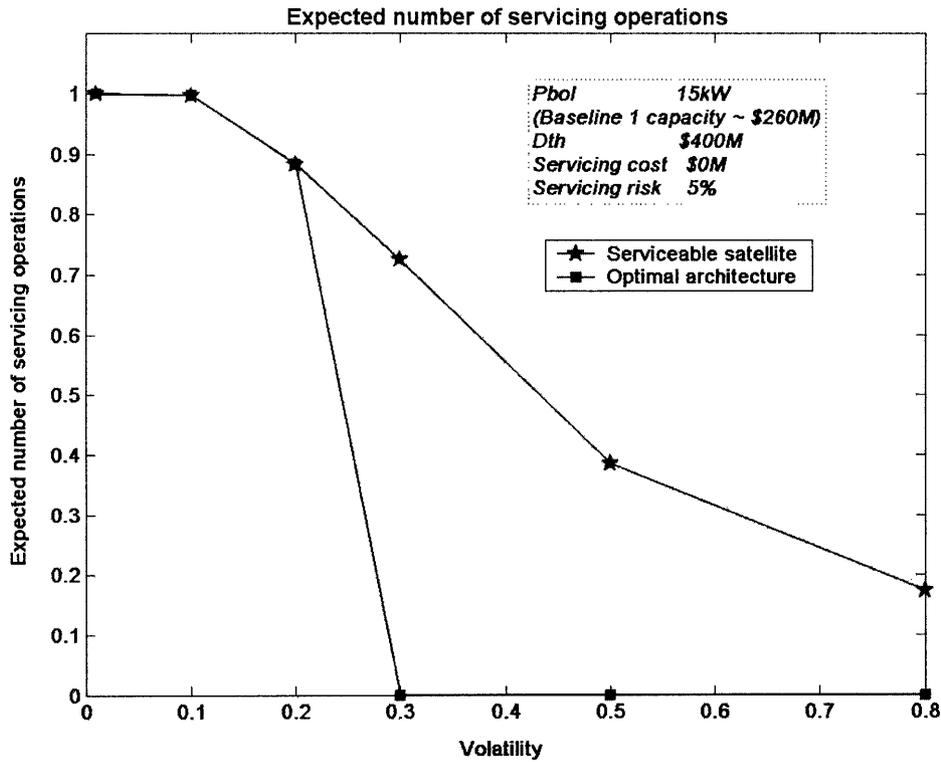


Figure 5-11: Average number of servicing operations demanded.

will be. This translates to determining the demand curve for a potential servicing market. The expected number of servicing operations for an initial demand level of \$400 million and a 5% servicing risk is shown in Figure 5-11 as a function of volatility for the Serviceable satellite and for the optimal architecture as seen in Figure 5-10. Designing for serviceability is the preferred option for volatilities below 30%. However, the corresponding demand for a servicing market never goes beyond an expected number of one servicing mission over the 15-year satellite lifetime. The demand for a servicing market appears very low in the case considered.

5.3.5 Servicing infrastructure characteristics

The demand for a servicing market can be determined as a function of the two main characteristics of the servicing infrastructure that are the servicing price and the servicing risk. Figure 5-12 shows such a demand curve for $D_f = \$260$ million. The characteristics for which demand for a servicing market exists are very restricted. The risk of servicing must

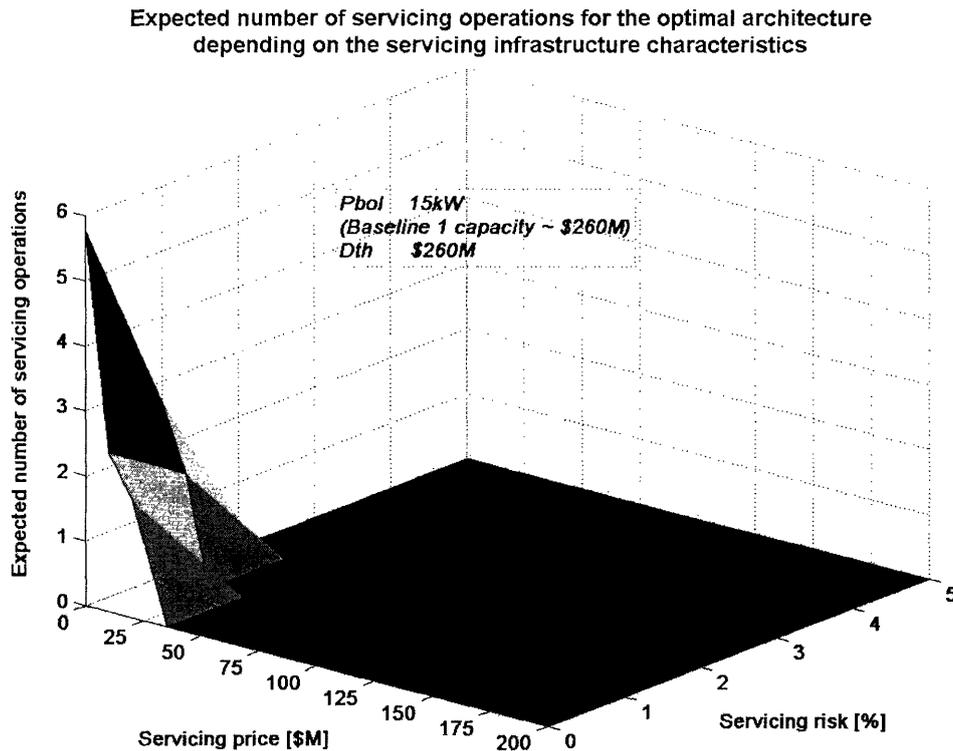


Figure 5-12: Expected number of servicing operations depending on the characteristics of the servicing infrastructure.

be reduced below 2% and the cost of servicing must not exceed \$40 million to generate some demand for on-orbit servicing. This seems to imply that the opportunity for the development of a servicing market and a profitable servicing infrastructure are very limited in the example considered.

5.3.6 Optimal architecture and BOL power

The previous results assumed a common BOL power for all architectures. In this section, the BOL power level is optimized to maximize the total expected value of the mission. Designing for a higher BOL power increases the satellite capacity and is an alternative to upgrading the solar panels. The trade off between the cost of designing for a higher BOL power and the cost and risk of servicing the satellite is investigated.

Figure 5-13 shows the optimal architecture and the optimal BOL power for different market conditions for a servicing risk of 0% and a servicing cost of \$0. Designing for serviceability

appears optimal for all conditions. The servicing operation is assumed to be performed at no cost and with no risk of failure. Therefore, the main penalty associated with a Serviceable satellite is the initial added cost to design for serviceability. Designing for serviceability is cheaper than designing a standard satellite for a higher BOL power or using InP solar cells to provide the same capacity. Therefore the Serviceable satellite is favored over other alternatives. It can be noted that even for a non volatile market ($\sigma = 0\%$), a Serviceable satellite is still preferred to a standard satellite. This choice may seem surprising at first since there is no need for flexibility when there is no uncertainty in the market. This surprising result is related to the fact that designing for serviceability offers a large cost advantage by reducing the required BOL power. This is largely dependent on the assumption of an ideal servicing infrastructure providing a service at no cost and no risk. For higher initial demand levels, a higher satellite capacity is desirable and the satellite is designed for a higher BOL power. As discussed in the previous results, as market volatility increases, the value of serviceability decreases, which translates into a lower BOL power. As the risk of failure of the servicing operation increases, designing for serviceability is less appealing and for some conditions, the space operator shifts towards less risky alternatives. Figure 5-14 shows the evolution of the optimal architecture for a servicing risk of 2%. For low initial demand levels and for low market volatilities, using highly resistant InP solar cells (Baseline 2) is preferred to designing the satellite for serviceability. The risk of losing the satellite during a servicing operation drives the choice towards Baseline 2, which is the second best architecture for these market conditions. As explained in Section 5.3.3, Baseline 2 is preferred to Baseline 3 with these market conditions because a high capacity is valuable later in the mission. Baseline 3 could be designed for a higher BOL power to provide the required capacity at end of life but this alternative is more expensive than choosing a Baseline 2 satellite. By comparing Figure 5-13 with Figure 5-14, it can be seen that the Baseline 2 satellite is designed for a higher BOL power than a Serviceable satellite would have been. A Baseline 2 satellite offers a lower capacity than a Serviceable satellite designed for the same BOL power. The space operator therefore provides extra capacity by designing Baseline 2 for a higher BOL power. The cost of increasing BOL power is preferred over the consequences of losing the satellite during a servicing operation. For a servicing risk of 5%, the serviceable architecture is never chosen as illustrated in Figure 5-15. Highly resistant solar cells are more often used and, for high initial demand levels

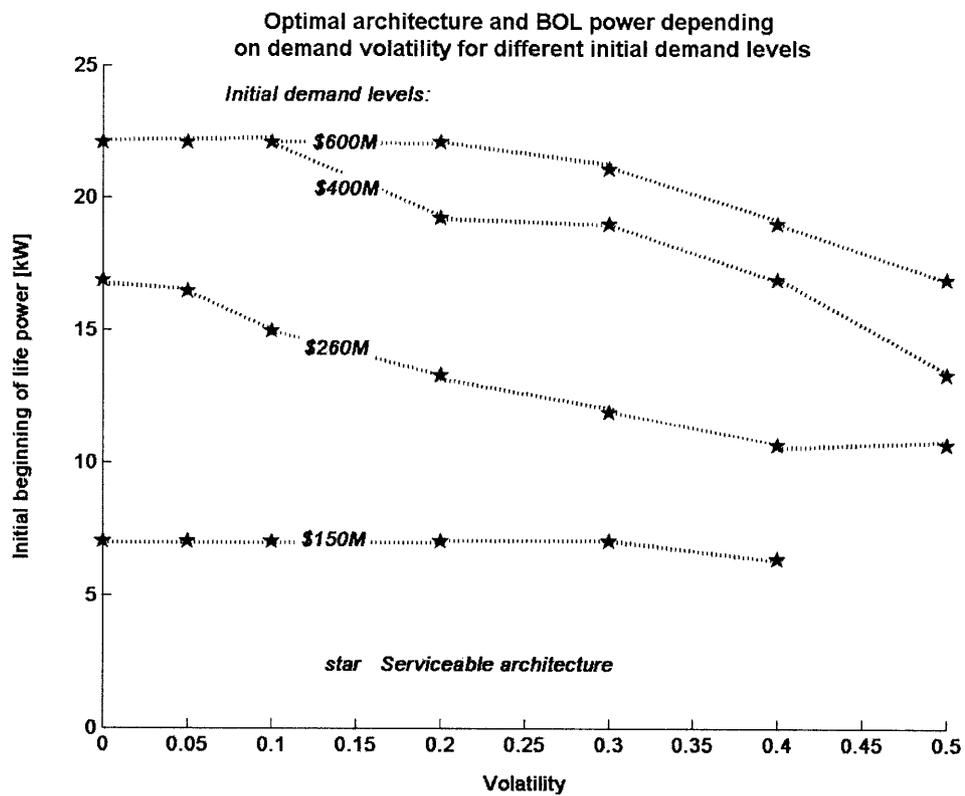


Figure 5-13: Optimal architecture and BOL power depending on initial demand level and market volatility for a servicing cost of \$0 and a servicing risk of 0%. (This is the best case scenario).

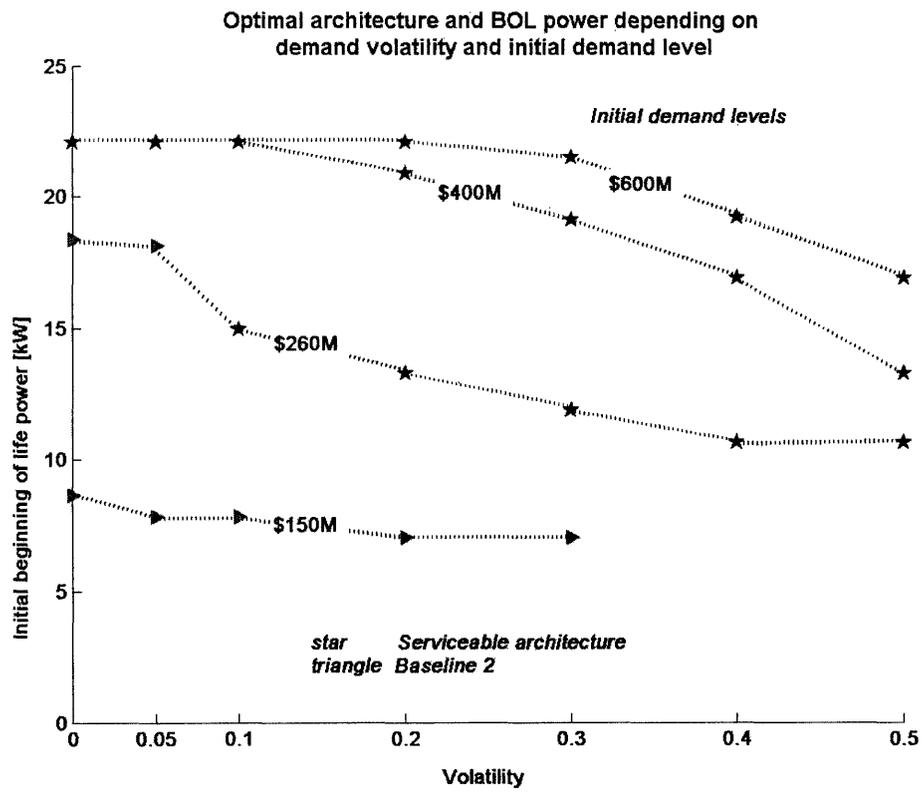


Figure 5-14: Optimal architecture and BOL power depending on initial demand level and market volatility for a servicing cost of \$0 and a servicing risk of 2%.

and high volatilities, the decision maker favors the design of a larger payload at beginning of life (Baseline 3). These results are similar to the trends described in Section 5.3.3. For high initial demand levels and high volatilities, a large capacity is desirable at the beginning of the mission, giving an advantage to a Baseline 3 satellite over a Baseline 2 satellite. A Baseline 2 satellite could be designed for a higher BOL power to provide the initial desired capacity level. However, this alternative is more expensive than designing a larger payload. Similar BOL power levels are seen for Baseline 3 satellites in Figure 5-15 and Serviceable satellites in Figure 5-13 because both architectures offer the same initial capacity levels for a given BOL power.

The main driver in determining the optimal architecture appears to be the large cost of designing for a higher BOL power. Designing for serviceability offers the opportunity to design for a lower BOL power and to maintain a high capacity when the state of the market is favorable. For a servicing risk above 5%, on-orbit servicing is not a viable concept in the case studied. In the results presented, the servicing operation is assumed to be free of charge. As the cost of servicing increases, the domain of predominance of the serviceable architecture will be further reduced.

5.4 Limitations of the model

The model presented only considers the market for telephony. GEO communication satellites are often used for other applications such as television broadcast or internet connection which are not considered in the calculation of the revenues. Most current GEO communication satellites have at least 1 or 2 broadcast channels which use a large part of the satellite power. In the model, the capacity of the satellite is considered to be entirely used to provide communication to end users. A more precise model could consider the case of a satellite serving two different markets, telephony and television broadcast, and estimate the effect of upgrading solar panels on revenues from both markets.

The assumption of a constant price per billable minute can be challenged in particular when demand far exceeds supply. The price of a billable minute is correlated with demand and the satellite capacity to serve this demand.

The main limitation of the model is to consider only restoring the beginning of life power and not increasing the available power. This assumption was chosen to study the simple

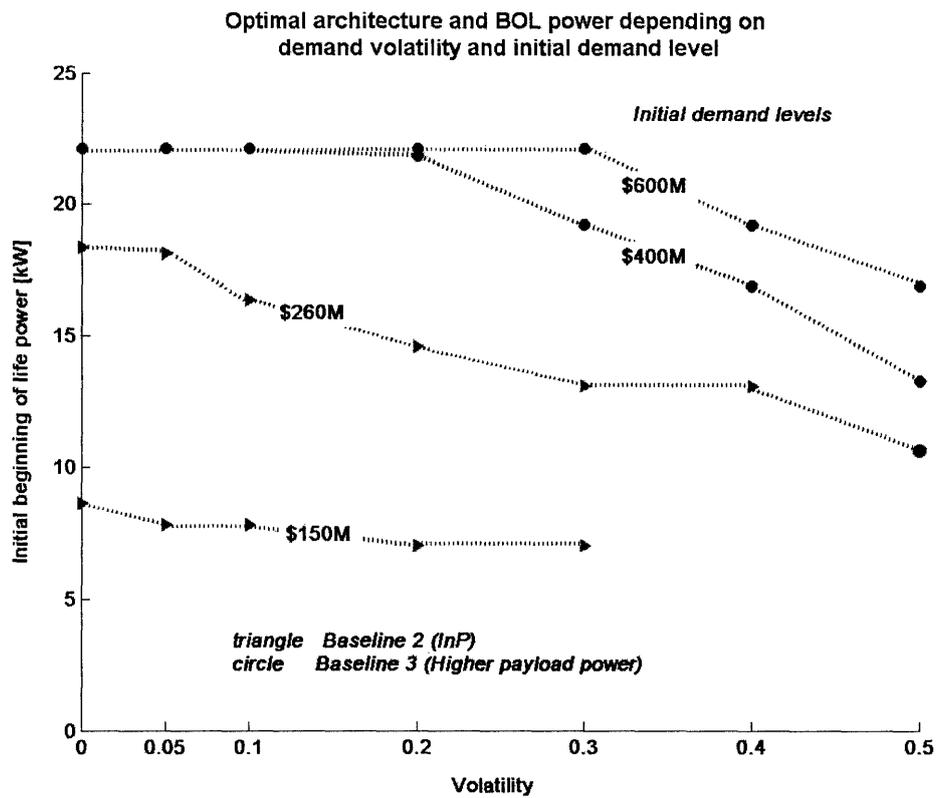


Figure 5-15: Optimal architecture and BOL power depending on initial demand level and market volatility for a servicing cost of \$0 and a servicing risk of 5%.

case in which only the solar panels are upgraded. The impact of the upgrade on the other subsystems is therefore limited and no consideration of compatibility is necessary. A more complex study could try to take into account the satellite modifications necessary to increase the on-board power above the maximum power level for which the satellite was designed. The main subsystems impacted would be the thermal management subsystem, the power distribution system, the batteries for delivering power during eclipse, the additional payload to benefit from the increase in power and potentially the attitude control subsystem if the increase in the solar panel surface is large. Increasing the power above BOL power would increase the effect of the upgrade on capacity and could therefore increase the value of the option to service as explained in Section 5.3.1 depending on the cost of upgrading the other constraining subsystems.

5.5 Conclusions

The case of the upgrade of solar panels on a GEO communication satellite to restore BOL power has been investigated. The servicing strategy has been compared to other alternatives such as building in highly resistant solar cells in the initial design, designing the satellite for a shorter lifetime and regularly replacing the satellite or designing the payload for a higher level of power and letting the capacity degrade as the on-board power declines. On the contrary to what is often seen in options theory, the value of the option offered by a serviceable architecture does not seem to always increase with volatility. For low volatilities, the option becomes more valuable as volatility increases. However, at high volatilities, a reverse trend is seen. It is believed that this behavior results from the assumption of a limited capacity. The flexibility offered by the serviceable architecture is limited in scope and can allow to take advantage of only a limited range of opportunities. The value of the flexibility seems to depend on the adequacy between the scope of the flexibility offered and the level of uncertainty faced.

Few conditions have been found for which on-orbit servicing appears attractive in the particular example studied. The expected demand for a servicing market is very low, in particular when considering a non zero servicing price and a risk of a catastrophic failure during the servicing operation. For a very low servicing cost and risk, designing for serviceability is optimal. However, as the risk and cost of a servicing operation increase slightly, the space

operator shifts towards less risky alternatives.

It is believed that on-orbit servicing does not appear very promising in this example because of two characteristics of the case studied. First, since the power on-board cannot be increased beyond the BOL power level, servicing only provides a small increase in mission capacity. On-orbit servicing therefore does not offer a great improvement compared to efficient alternative methods such as the use of highly resistant solar cells in the initial design. Moreover, solar panel degradation is a predictable phenomenon. Alternative technological solutions can shield against such degradation.

As a conclusion, on-orbit servicing is not attractive because the increase in mission utility due to the upgrade is small compared to a non flexible mission and there exist cost effective and less risky alternatives to provide a similar increase in utility. Thus, technology upgrade could be a more promising application since innovation can significantly increase utility and there may not be more cost effective methods to install a new technology that appears after the satellite is deployed.

Chapter 6

Upgrade of a scientific mission: the Hubble Space Telescope (HST)

Launched in 1990, the Hubble Space Telescope (HST) is the only example of an unmanned platform designed to be regularly serviced by the Shuttle. A modular design was adopted to allow repairing the telescope, installing new payload instruments and regularly upgrading bus components to make Hubble a state of the art scientific observatory. The Hubble Space Telescope is a unique opportunity to analyze a real serviceable platform and use real data to investigate the value of satellite upgrade using on-orbit servicing. The model of a serviceable scientific mission is developed on the basis of the Hubble Space Telescope example. Three types of servicing missions are considered: the repair of the spacecraft, the upgrade of the payload instruments and the upgrade of other bus subsystems. The history of the Hubble servicing missions is first reviewed to give the context of the study before describing the model developed. The value of the option to repair and to service are then investigated using the data from the HST manned servicing missions. The impact of different design choices on the value and cost of the mission are presented. We then analyze the main differences between manned and unmanned servicing missions in an attempt to derive conclusions for robotic on-orbit servicing of scientific missions.

6.1 Hubble Space Telescope (HST)

The Hubble Space Telescope, orbiting at 600 km above the Earth, has revolutionized our understanding of the universe. Hubble's accomplishments include for example astonishing

pictures of galaxies, black holes and other objects in the Universe, more precise estimations of distances to far-off galaxies and new evidence in the controversial issue of the expansion of our universe. Every day, Hubble stores between 3 and 5 gigabytes of data and generates between 10 and 15 gigabytes of data delivered to astronomers all over the world [23]. The observatory is undoubtedly a great success as illustrated by the large demand for observation time, five times higher than the available time [8]. The great achievements of the Hubble Space Telescope mission have been possible because of the regular upgrades and repairs of the spacecraft.

6.1.1 History

The Hubble Space Telescope was designed in the 1970s and deployed on April 25th 1990 by the Shuttle Discovery. A spherical aberration in the primary mirror was discovered immediately and corrected during the first servicing mission. A total of four servicing missions has been performed to make the Hubble Space Telescope a state of the art observatory along the 13 years it has been operated. A fifth servicing mission is planned in 2005. The number of servicing missions that should be planned beyond 2005 is currently debated. The option to continue maintaining and upgrading the Hubble Space Telescope is compared to the alternative of investing in the development of a new modern platform. The James Webb Space Telescope is currently planned as a replacement for the Hubble Space Telescope.

The Space Telescope Science Institute was created in 1981 as the astronomical research center for the Hubble Space Telescope in charge of programming Hubble's observation schedule and organizing the release of the data generated.

An interesting issue to the present study is the circumstances leading to the decision to design the telescope to be regularly serviced. First, the emergence of the Shuttle, a reusable vehicle capable of reaching orbit and returning to Earth, was an enabler for on-orbit servicing. The first concept of what would be the Hubble Space Telescope emerged in 1969 with the approval by the National Academy of Sciences of the Large Space Telescope (LST) program. At that time the capability offered by the Shuttle was not available. With the development of a reusable vehicle, two concepts were proposed: the telescope could be regularly returned to Earth using the Shuttle to be repaired and upgraded on Earth or the repair and upgrade operations could be done in orbit by astronauts. The second more innovative concept was chosen. However, if the Shuttle has been an enabler of on-orbit servicing, it

does not explain the need for serviceability. The rationale for designing the Hubble Space Telescope for serviceability was to reproduce in space the equivalent of an observatory on Earth [8]. On Earth, instruments can be changed as more efficient instruments appear and as the state of knowledge evolves requiring different types of measurements or different targets to be studied. The HST modular design was chosen because it offers a way to adapt the observatory to the need of the scientific community and to prevent technical obsolescence over the long lifetime characterizing a space platform.

6.1.2 Servicing missions

Five servicing missions have been planned, the last one to be launched in 2005. Three main types of operations were conducted: the repair of satellite subsystems, the installation of new instruments and the upgrade of other critical satellite components. A review of some selective operations conducted during each servicing mission is presented to highlight the main accomplishments made possible by on-orbit servicing [26]. Initially five instruments were implemented on the observatory: the Wide Field Planetary Camera 1 (WFPC1), the Goddard High Resolution Spectrograph (GHRS), the Faint Object Spectrometer (FOS), the Faint Object Camera (FOC) and the High Speed Photometer (HSP). The evolution of the instruments on board Hubble is summarized in Figure 6-1.

Servicing mission SM1 Launched in December 1993, the first servicing mission is most famous for the correction of the optical flaw on Hubble's primary mirror.

- **Repair:** The outer edge of the primary mirror was too flat by a depth of 2.2 microns causing all images to be blurred because some light from the target objects was scattered [26]. The COSTAR (Corrective Optics Space Telescope Axial Replacement) was installed in place of one of the instrument (the High Speed Photometer) to compensate for the effect of the optical aberration with corrective mirrors. Other repair operations were carried out such as the installation of new magnetometers or the addition of a more rigid structure to the flexible solar panels to reduce the vibrations due to their oscillation.
- **Instruments:** The High Speed Photometer was taken out because the slot was needed for the COSTAR. The Wide Field Planetary Camera 2 (WFPC2) was installed in

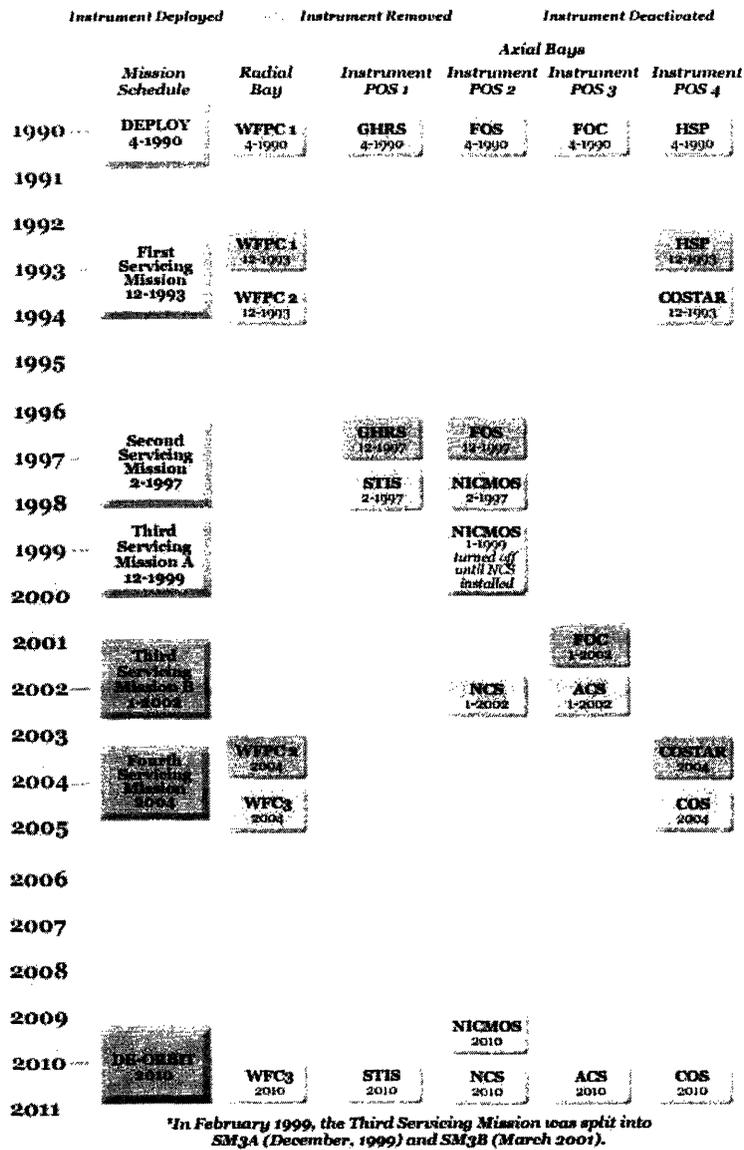


Figure 6-1: Evolution of the scientific instruments on-board the Hubble Space Telescope [25]

replacement of the WFPC1 and offered significantly improved performance in the ultraviolet domain [26].

- Upgrade of other subsystems: Among many upgrades, coprocessors for the flight computer and additional memory were installed to increase the computation power of the telescope. The initial computer, equivalent to an Intel 286, was upgraded to the equivalent of an Intel 386.

Servicing mission SM2 The second Servicing mission was launched on February 1997 and significantly improved the performance of the observatory with increased memory and new instruments.

- Instruments: The new spectrograph STIS (Space Telescope Imaging Spectrograph) allows gathering 30 times more spectral data and 500 more spatial data than the previous spectrograph GHRS on Hubble [26] and is of particular interest in the study of black holes. The second instrument installed is the NICMOS (Near Infrared Camera and Multi-Object Spectrometer). This instrument new capabilities have enabled the observation of objects that were too distant for the previous optical and ultraviolet instruments.
- Upgrade of other subsystems: The main upgrade is the installation of solid state recorders that can store ten times more data than the previous subsystem.

Servicing mission SM3A The third planned servicing mission was split in two Shuttle flights, SM3A and SM3B, after the failure of three of Hubble six gyroscopes. Three gyroscopes are required to control the pointing of the telescope. The failure of a fourth gyroscope prevents any observation to be done. After the failure of three of Hubble's gyroscopes, a repair mission SM3A was launched in emergency in December 1999, earlier than originally planned. The new instruments planned to be installed during the third servicing mission were not ready and were launched on a later Shuttle flight SM3B. The servicing mission SM3A was approved and developed in only seven months. The failure of a fourth gyroscope shortly before the launch of the servicing mission forced NASA to put Hubble in safe mode for a few months during which no observation was possible.

- Repair: The main task was to repair the gyroscopes to restore Hubble's pointing

capability. The thermal blanket was also repaired after astronauts in SM2 discovered degraded areas on the outer blanket layer.

- Upgrade of other subsystems: Even if no new instruments were installed, the servicing mission significantly increased the performance of the observatory. In particular the astronauts installed a new advanced computer that was 20 times faster and had six times as much memory as the previous on-board computer designed in the 1970s. The recording system was also enhanced with the replacement of tape recorders with solid state recorders. They are more reliable since they do not have moving parts and can store 12 gigabytes of data (as much as 10 times more data).

Servicing mission SM3B A fourth visit to the Hubble Space Telescope was done on March 2002. Three main operations were carried out:

- Instruments: The new camera ACS (Advanced Camera for Surveys) was installed that operates in the visible and ultraviolet. ACS offers a high resolution and a wide field of view therefore increasing the discovery efficiency (product of field of view and throughput) of WFPC2 by a factor 10. NICMOS was returned to operation after repairing its cooling system with the NCC (Nicmos CryoCooler).
- Upgrade of other subsystems: The third main operation conducted was the upgrade of the solar panels. New rigid solar arrays were installed that are more robust, less subject to drag because of their smaller size and that produce 30% more power.

Servicing mission SM4 The last servicing mission is planned to be launched in late 2004 or 2005. Two new instruments have been approved: the Wide Field Camera 3 (WFC3), a new generation imaging camera, and the Cosmic Origins Spectrograph (COS) designed to observe the new and mid ultraviolet.

6.1.3 Value of serviceability

The example of the Hubble Space Telescope illustrates the large benefits derived from a serviceable platform that can be repaired and maintained but also upgraded to follow the evolution of technology and user needs.

Mission salvage

The ability to service the Hubble Space Telescope made it possible to save the mission. The flaw in the primary mirror would have significantly reduced the scientific usefulness of the space telescope and the failure of four of the six gyroscopes would have caused the mission to be lost. Serviceability offers an insurance against a potential loss of the mission. Similar cases of unpredicted failures have been experienced in other missions. For example, the Chandra X-ray Observatory, which is not designed for serviceability, experienced a problem with the sensitivity of the main X-ray detector in the beginning of the mission. A solution could be improvised to mitigate the problem by closing the detectors when crossing the radiation belt. However, in some cases the mission may not be recoverable without a physical repair, such as in the case of the Hubble telescope, making on-orbit servicing particularly attractive.

Repair and maintenance

Extensive maintenance operations were conducted to ensure the health of the Hubble spacecraft. Two characteristics of the repair missions should be emphasized. First, on-orbit servicing has allowed to repair problems that were not expected in the initial design of the vehicle. The thermal blanket degraded faster than expected and had to be replaced after the astronauts on mission SM2 discovered the issue. It was not expected that the flexible structure of the solar panels would cause them to oscillate creating disturbances in the observations. Another illustrative example is the case of the gyroscopes that appear to be the largest failure point of the spacecraft and are failing far more rapidly than it was expected. Secondly, on-orbit servicing has provided a way to return the failed components back to Earth to study the causes of failure and find solutions to fix the unexpected problems. This was mainly possible because of the use of the Shuttle.

Instrument upgrade

The upgrade of the instruments extended the possibilities of the observatory by incorporating state of the art instruments and new capabilities. A total of twelve instruments will be installed on Hubble offering improved performance and different observation capabilities.

Improvement Trend In Performance Parameters

	Launch	SM1	SM2	SM3A	SM3B	SM4
Data Storage (G Bits)	3	-	12	21	-	-
Computer Processing Power (MIPS)	0.35	4.55	-	91.00	-	-
Total Avail. Power (W)	2495	2495 ¹	2270	2150	² 2835	2770 (est)
Power Avail. To SIs (W)	1080	1190	1035	1000	1760	1640 (est)
Power Required by SIs (W)	500	465	690	655	1260	1505 (est)
AR Shroud Heat Transport - Radiated	531	466	566	-	695	645
AR Shroud Heat Transport - Conducted	0	-	-	-	345	510
Peak Science Jitter (mas, 60-second rms) all disturbances	39	23	-	-	14	-
Peak Science Jitter (mas, 60-second rms) disturbances occurring at least once per orbit	36	21	-	-	6	-
Quiescent Science Jitter (mas, 60-second rms)	3 30% of orbit time	3 35% of orbit time	-	-	3 95% of orbit time	-
Cryogenic Cooling	None	None	Frozen nitrogen 70K	None	Mechanical cryocooler 74K	None

Figure 6-2: Main improvements in the Hubble spacecraft performance through bus upgrades [29].

Other bus upgrades

Upgrading other subsystems to implement new technologies has radically increased the performance of the observatory and made the installation of new instruments possible. The upgrade of the solar panels and the thermal system made it possible to operate up to four instruments simultaneously, compared to only two in the initial design. The performance of the spacecraft computer and the available on-board memory have greatly increased over time. The speed of the on-board computer and the data archiving rate have been multiplied by respectively 20 and 10 through the four servicing missions. Computer modules appear as good candidates for upgrade because of the fast pace at which computer technology evolves. The main improvements in the spacecraft performance through bus upgrades are illustrated in Figure 6-2 [29].

6.1.4 Decision model for upgrades

A competitive process is followed to decide on the upgrade of scientific instruments. Different proposals are submitted describing potential new instruments, the new observing capability they offer and how they would integrate within the mission objectives of the Hubble Space Telescope. A panel of astronomers reviews and evaluates the different propositions and decides on which instrument will be installed during the next Shuttle visit. Three main parameters are considered when choosing the instruments to be taken out of the observatory: the existing demand for observation time within the astronomy community, the concern of keeping a balance between the different categories of instruments on-board the observatory and the expected performance and reliability of the instrument over the following years. The upgrade of bus subsystems are often required to operate the new instruments.

6.2 Presentation and objectives

6.2.1 Presentation

The model has been constructed from the example of the Hubble Space Telescope and aims at estimating the value of serviceability for a scientific mission. A single instrument is assumed to be installed on the satellite. A utility metric is defined to capture the scientific return of the mission. Utility depends on the generation of the instrument installed on the satellite and on its compatibility with the other on-board bus subsystems. Three potential servicing operations are considered: the repair of the spacecraft, the installation of new instruments and the upgrade of bus subsystems. The decision to upgrade or repair is made if the utility per cost metric exceeds a predefined threshold. Data from the Hubble Space Telescope are used to benefit from real inputs from an existing serviceable mission. In particular we used the probability of failure of the spacecraft, the instruments utility and the servicing costs. A Monte Carlo simulation is used to model four sources of uncertainty: the appearance of a new instrument, the emergence of a new technology for a bus upgrade, the failure of the spacecraft and the potential failure of a servicing operation. Different levels of flexibility are investigated from a non serviceable to a fully serviceable spacecraft.

6.2.2 Objectives of the model

The main questions investigated are:

- What is the potential improvement in utility that can be achieved with serviceability?
- What are the respective contributions from satellite upgrade and from satellite repair?
- How does servicing risk affects the value of servicing?
- What is the impact of the pace at which technology evolves?
- What is the impact of the decision model defining what upgrade and repair are conducted?
- To what extent can the data from the Hubble Space Telescope be used to derive conclusions on the value of unmanned on-orbit servicing?

6.3 Assumptions and model description

6.3.1 Valuation method: Monte Carlo simulation

The choice of the valuation method is tightly related to the goal of the decision maker. In the case of a scientific mission, it is considered that the decision maker is more interested in maximizing current rather than future value of the utility metric. On the contrary to a commercial space operator, who is interested in maximizing the return on mission by maximizing profits over the entire lifetime of the satellite, the scientific community would concentrate on obtaining the maximum scientific return at each period within a maximum cost cap or specific cost constraints. As a consequence, the optimal decision at a point T in time can be determined without determining in advance what is optimal at later periods. A forward process can be adopted starting at the first decision point and advancing towards the end of the time horizon.

A Monte Carlo simulation is used to take into account the different sources of uncertainty and estimate the value of flexibility. A probabilistic distribution is chosen to characterize each uncertainty parameter. A simulation corresponds to one run of the model over the lifetime of the satellite to calculate the total utility, the discounted costs and the sequence of decisions chosen. At each decision point during the simulation, each uncertainty parameter

is assigned a value that is a random draw within its distribution. Each run corresponds to a possible scenario of resolution of the uncertainty over the time horizon. In a Monte Carlo process, a large number of simulations are run to generate a representative set of possible outcomes. The distributions of utility and costs are derived from the frequency of occurrence in the large sample of simulations.

6.3.2 Uncertainty

Four sources of uncertainty are incorporated in the model: the uncertainty in the appearance of new instruments or new technologies and the uncertainty in the failure of the spacecraft or a servicing operation.

Uncertainty in the evolution of instrument technology

A new instrument corresponds to a technological improvement and therefore an increase in the performance of the instrument. The arrival of a new instrument is uncertain and represented by the probabilistic variable X_I , with $X_I = 1$ when a new instrument is invented and $X_I = 0$ otherwise. X_I is assumed to follow a Poisson process with a mean time of arrival T_I . The probability of a new instrument being invented in the time interval dt is:

$$P(X_I = 1) = \lambda_I dt = \frac{1}{T_I} dt \quad (6.1)$$

In most of the calculations, the mean time between new instruments is assumed to be 4 years because the mean time between the installation of new instruments on the Hubble Space Telescope is 4 years. An instrument is characterized by its generation, which is its rank of appearance. The initial instrument installed corresponds to generation 1. If the current state of the art instrument is generation d , a new instrument will be generation $d + 1$.

Uncertainty in the evolution of technology for bus upgrades

Evolution in technologies can lead to improvements in the performance of subsystems other than the payload. The arrival of such a new technology is uncertain and is represented by the probabilistic variable X_B , with $X_B = 1$ when a new upgraded module is available and $X_B = 0$ otherwise. X_B is assumed to follow a Poisson process with a mean time between

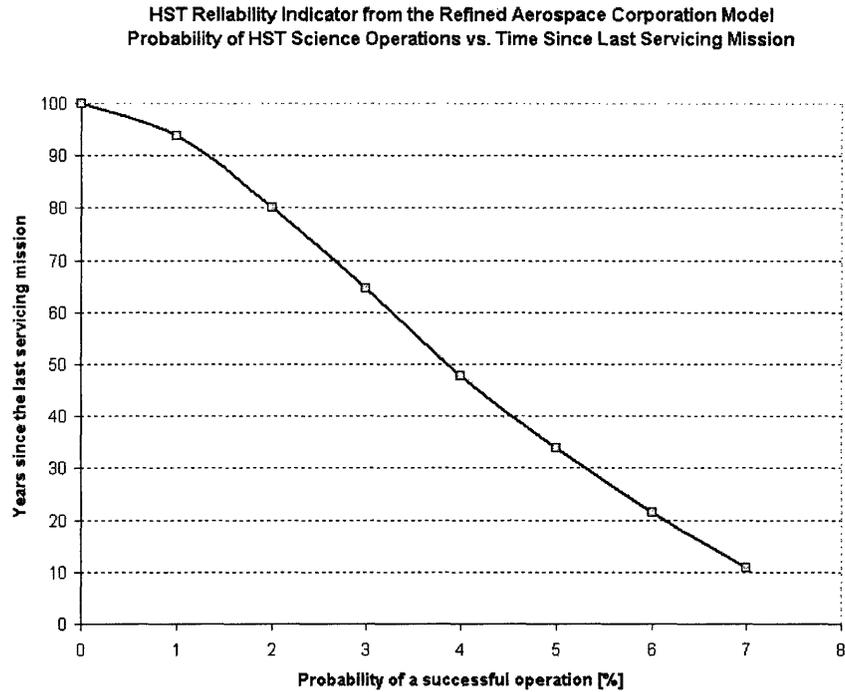


Figure 6-3: Hubble Space Telescope reliability depending on the time elapsed since the last repair mission [18].

arrival noted T_B . The probability of a new bus subsystem improvement being invented in the time interval dt is:

$$P(X_B = 1) = \lambda_B dt = \frac{1}{T_B} dt \quad (6.2)$$

As for instruments, bus technologies are characterized by their generation, which is the rank at which they are invented. The state of the art bus technology when an instrument d is invented is noted N_B^d .

Spacecraft failure rate

The probability of a successful operation of the satellite decreases as the time elapsed since the last repair increases. The evolution of the probability of success of the operation of the satellite P_S , shown in Figure 6-3, is taken from data on the Hubble Space Telescope reliability [18]. A failure is assumed to prevent any observation to be conducted and the spacecraft is of no utility to the user until the satellite can be repaired.

Uncertainty in the success of a servicing operation

The probability of success of a servicing operation is noted P_S^{Serv} . The failure of a servicing operation is assumed to be catastrophic and to cause the loss of the target satellite. The satellite cannot be repaired and no additional utility is generated over the rest of the time horizon.

6.3.3 Flexibility

The baseline architecture chosen as a reference is a satellite that cannot be serviced. No repair and no upgrade is possible. With a serviceable architecture, three independent decisions are offered to the space operator.

- Satellite repair: The satellite can be repaired restoring the reliability of the satellite to 1.
- Instrument upgrade: A new instrument can be installed. Since a single payload slot is considered, the previous instrument is turned off and replaced by the new instrument. The payload state of the art is defined as the latest instrument invented. The on-board payload technology is the actual instrument installed on the satellite. The space operator can choose to upgrade the satellite by installing any instrument that has a more efficient technology than the on-board instrument.
- Bus upgrade: The space operator can upgrade the bus subsystems. Again the state of the art technology refers to the latest innovation while the on-board technology is the last technology installed on the satellite. If the space operator decides to upgrade the bus subsystems, only the state of the art technology can be installed.

The decision maker can choose not to service the satellite or to carry any combination of these three operations. A servicing mission requires a single visit to the target satellite, independently from the number of operations conducted.

6.3.4 Utility

Choice of the utility metric

The utility characterizes the scientific return gained from the operation of the satellite and should be chosen carefully. Different metrics have been used by scientists to capture

the scientific return gained by the operation of the Hubble Space Telescope.

The number of papers published per year is sometimes used as a surrogate for scientific discoveries. This metric provides an estimate of the aggregate utility of the Hubble mission. However, the impact of an individual instrument is difficult to isolate. Four and sometimes five instruments were operational at the same time on the observatory and most of the papers refer to complementary observations carried out on different types of instruments. Moreover, the number of publications is highly dependent on the time the instrument has been operated on Hubble and on the date at which the instrument has been installed. Therefore the choice of this metric may create a bias towards older instruments and instruments operated for a longer period.

We chose to characterize the utility of an instrument by its discovery efficiency, a metric more related to the characteristics of the instrument. This measure, often used to describe and compare the capacity of observation cameras, is defined as the product of the field of view and the throughput of the instrument. The field of view characterizes the space that is viewed by the instrument whereas the throughput is a measure of the detection sensitivity of the instrument.

The discovery efficiency offers the advantage of being specific to the instrument and to characterize the performance of the instrument. However, the limitations associated with the use of this metric must be acknowledged. First, the discovery efficiency only applies to cameras and not to spectrographs or spectrometers. Moreover, the discovery efficiency varies with the wavelength used for the observation. An instrument can be used over a range of wavelengths and different cameras have different observation domains that may not be overlapping. The attribution of a single value for the discovery efficiency of an instrument and the comparison of different cameras operating over different domains may be difficult. Discovery efficiency values were chosen to characterize the cameras installed on the Hubble Space Telescope (WFPC1, WFPC2, ACS and WFC3) based on the limited data found. The discovery efficiency of a camera is chosen as the maximum discovery efficiency of the instrument at the two wavelengths 3000\AA and 6000\AA [4]. The NICMOS camera was not considered since it operates over different wavelengths. Table 6.1 summarizes the utility values used in the model. Using the utility data from the HST instruments, a utility curve is derived to characterize the increase in instrument performance provided by each innovation. Two different shapes have been considered: a polynomial fit referred to as the Smooth utility

Characteristics of Hubble cameras

Camera	Utility	Cost
WFPC1	1	\$130M
WFPC2	14	\$127M
ACS	110	\$75M
WFC3	180	\$83M [30]

Table 6.1: Estimates of the discovery efficiency and cost of the cameras installed on the Hubble Space Telescope.

curve and an S-shaped utility curve as illustrated in Figure ???. The model does not consider the instrument performance degradation over time. The utility gained is constant over the period of operation of the instrument.

Impact on utility of the upgrade of bus subsystems

In the model, the upgrade of bus subsystems does not increase the utility of an instrument. The discovery efficiency defined previously is considered as the maximum utility the instrument can provide per year of operation. When a new instrument is developed, we assume that the instrument is designed for the current state of the art bus technology. For example, the bus processor requirements of a new camera will correspond to the characteristics of the state of the art processors implemented in newly designed satellites. The performance of an instrument is assumed to be optimal if the satellite bus subsystems incorporate technologies at least as efficient as the technology that was the state of the art when the instrument was developed. If a new instrument is installed and the bus subsystems are not upgraded to the state of the art bus technology, the instrument is assumed to be constrained by the bus subsystems and a lower utility is provided. The decrease in utility depends on the number of innovations that separates the on-board technology and the technology for which the instrument has been designed. The actual utility u^d gained for a year of operation of the instrument d is given by:

$$u^d = u_m^d e^{-\left(\frac{N_B^d - N_B}{N^{re}J}\right)^2} \quad (6.3)$$

where u^d is the actual utility per year of operation of the instrument, u_m^d the maximum utility per year of operation for an ideal performance of the instrument, N_B^d the generation of the bus technology that was the state of the art when the instrument d was developed,

N_B the generation of the bus technology used on-board the spacecraft and N^{ref} a reference parameter that defines the rate of decrease of the instrument utility as a function of bus technology obsolescence.

Impact of servicing missions on utility

If an upgrade mission is demanded, the increase in utility is taken into account in the period at which the decision to upgrade is made. Moreover, upgrading the satellite does not significantly impact the operation of the spacecraft and no down time is considered. A preventive mission launched to repair the satellite before a failure occurs does not impact the operation of the satellite either and a full utility is gained. In case of a satellite failure, no utility is gained over the period if the satellite is not repaired. If a repair mission is launched, the satellite is assumed not to be operational for 25% of the period to take into account the time to repair.

6.3.5 Costs

Repair cost The cost of repairing the spacecraft, not including the price of the servicing mission, is assumed to be proportional to the probability of failure of the spacecraft. As a reference, we chose to set the cost of repairing the satellite four years after the last repair mission at \$70 million, based on data from Hubble repair missions. The Hubble Space Telescope was repaired approximately every four years and a typical repair cost is derived from the hardware and software expenses incurred during the servicing mission SM3A [28]. The repair cost is therefore given by:

$$C_{rep} = \frac{70}{P_f(4)} P_f(t) \quad (6.4)$$

where $P_f(t)$ is the probability of failure of the spacecraft t years after the last repair mission and $P_f(4)$ equals approximately 50% given the reliability of the Hubble Space Telescope.

Instrument cost Some estimates of the cost of the cameras installed on Hubble is shown in Table 6.1. The trend is towards a decreasing cost of the instruments and each new instrument appearing after WFC3 is assumed to cost \$100 million.

Other cost assumptions The cost of the initial satellite is set at \$1 billion similar to the cost of the Hubble Space Telescope. A cost penalty of 10% is assumed to design the satellite for serviceability. Operation costs are set to \$21 million per year. Any bus upgrade is assumed to cost \$20 million based on some estimates of the cost of bus upgrades on the Hubble Space Telescope (the advanced computer was estimated at \$7 million and new state recorders at \$11 million). Finally, similarly to the Hubble Space Telescope, it is assumed that the spacecraft does not have thrusters on-board to deorbit at end of life and a servicing mission is required to place the dead satellite on a graveyard orbit or on a trajectory to reenter and burn in the atmosphere. This termination mission is not required if a catastrophic failure occurred during a servicing mission.

6.3.6 Decision model

The decision model used to determine if a repair or an upgrade mission is launched is illustrated in Figure 6-4.

Scheduled repairs Scheduled repairs are planned to prevent the satellite reliability to decrease below 50%. This corresponds to regular repair missions every 4 years if no on-demand repair mission is carried out.

Repair and upgrade If the satellite is visited for an instrument or bus upgrade, it is assumed that the satellite will be repaired at the same time and restored to a 100% reliability. The cost of the hardware necessary for the repair is small compared to the cost of the servicing mission. Moreover, the major source of risk is the docking of the servicer to the target which is already necessary for the other missions performed. Therefore, once a servicing mission is planned, the satellite is fully repaired.

Decision model sequence First the space operator examines if a repair mission is required. A repair mission is needed if the satellite fails during the period considered, if the satellite has failed in previous periods and has not yet been repaired or if a scheduled repair is planned to prevent the reliability of the satellite to drop below the predefined threshold. Technology upgrade is then considered. An upgrade is decided if the utility per cost metric exceeds a minimum threshold. The utility per cost metric is defined as the ratio of the additional utility provided normalized to the utility gained with current technologies and

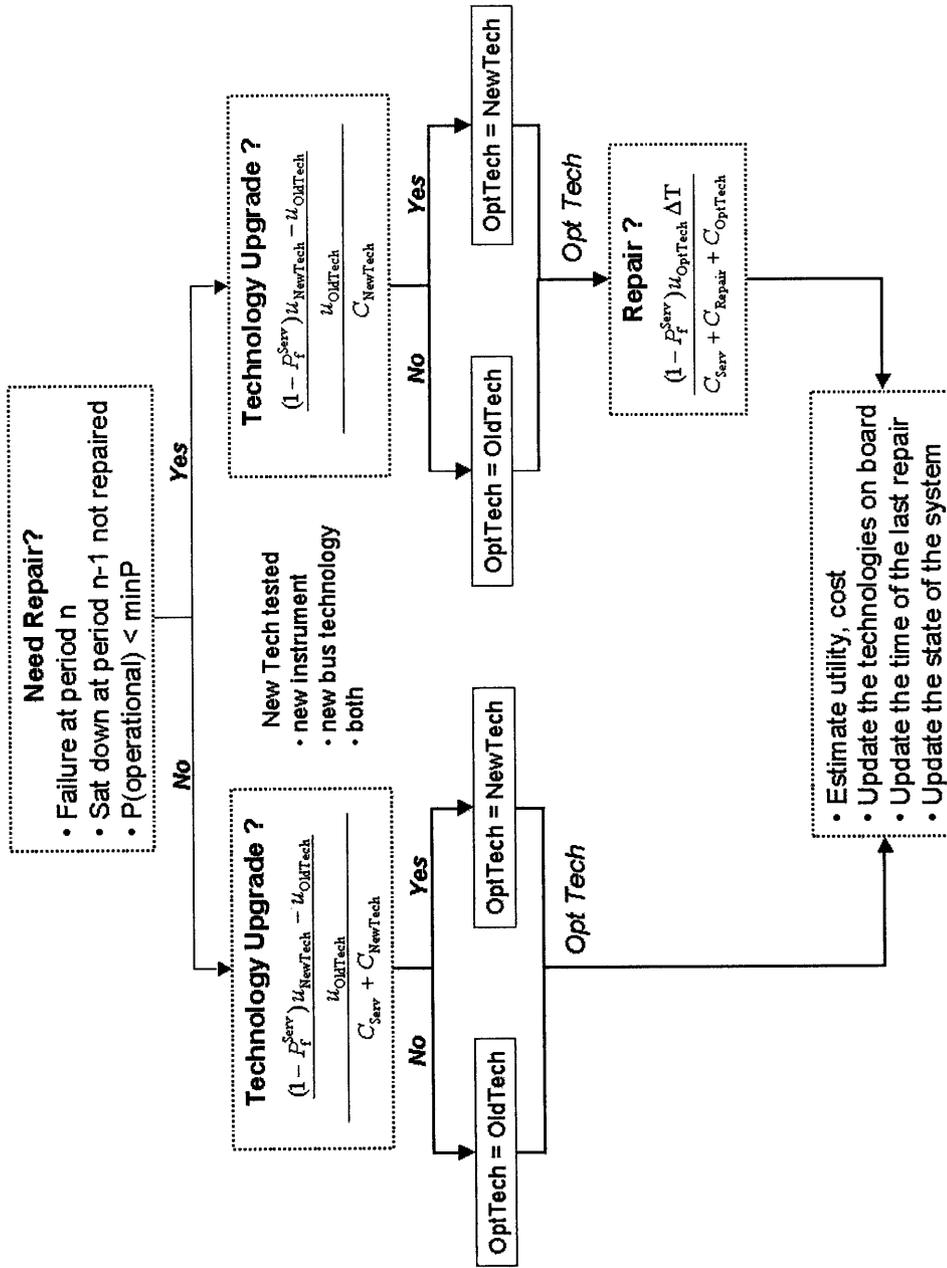


Figure 6-4: Decision model for the repair and upgrade of the spacecraft.

the cost of upgrading. If a repair mission is necessary for the health of the spacecraft, the price of the servicing mission will be incurred whether the satellite is upgraded or not. The decision maker decides if the satellite should be upgraded during the repair mission. Therefore, the cost of the servicing mission is not taken into account in deciding to upgrade. In this case the cost used to calculate the metric is only the cost of the new technology. The utility gained with an upgrade is multiplied by the probability of success of the servicing operation to take into account the risk of on-orbit servicing in the decision making. The decision maker is assumed to be risk neutral and to use the expected utility to make his decision. Different combinations of upgrades are considered with the installation of a new instrument if the state of the art payload is not installed on-board the satellite or/and a bus upgrade if a new bus technology is available. The optimal decision concerning the upgrade of the satellite is derived.

If a repair mission is necessary, the decision maker must then decide if the utility gained by the repair is sufficient to justify the cost of servicing the satellite. The servicing mission is launched if the utility metric, defined as the ratio of the utility gained until the next scheduled repair ΔT and the total cost of the servicing mission, exceeds a minimum threshold. The period until the next scheduled repair is defined as the minimum between the time remaining until the end of the satellite lifetime and the time until the satellite was planned to be repaired. The decision maker is assumed to take into account ΔT in his decision to service: servicing missions will not likely be launched near the end of the mission or if a servicing mission is already planned in a near future. The utility corresponds to the utility of the optimal technology that will be installed. Costs include the price of the servicing mission, the cost of the repair units and the cost of the upgrade if an upgrade was decided. Depending on the decisions made for the upgrade and repair of the mission and on the success of a servicing mission at that period, the utility gained and the costs incurred over the period until the next decision point are calculated. The technology installed on-board and the reliability of the satellite are updated if necessary.

6.4 Results

Most of the results shown in the following sections have been derived using the main assumptions summarized in Table 6.2.

Numerical assumptions	
Parameter	Value
Number of runs in the Monte Carlo simulation	1500
IOC cost	\$1000M
Cost penalty for serviceability	10%
Satellite lifetime	15 years
Operation costs	\$21M
Downtime penalty for satellite failure	25%
Reliability threshold for scheduled repairs	50%
Servicing cost	\$400M
Mean time of arrival of new instruments	4 years
Mean time of arrival of new bus technologies	2 years
Discount rate	7%

Table 6.2: Numerical assumptions for the analysis of the repair and upgrade of a scientific mission.

6.4.1 Utility probability distribution

In this section, examples of distributions obtained with the Monte Carlo simulation are presented to capture the effect of utility assumptions and servicing risk assumptions on the results.

Example of a utility distribution from a Monte Carlo simulation

Figure 6-5 illustrates a typical result from the Monte Carlo simulation, showing the probability distribution of the total mission utility that can be achieved with a serviceable satellite, normalized to the utility provided by a baseline satellite. In this case, the satellite is always repaired and upgraded to the latest technology. There is no risk of failure when the satellite is serviced and only the cameras installed on Hubble are considered as potential instruments. The probability shown on the y axis is calculated from the frequency of occurrence of a given utility value over the 1500 runs done during the Monte Carlo simulation. It can be noted that significant improvements in utility can be realized. New instruments provide a huge improvement in performance sometimes multiplying discovery efficiency by a factor of 10. A maximum utility improvement of 2105 is achieved when a new instrument appears every year for the first 4 years and the baseline satellite fails during the first year of operation. The scale is artificially large because of the utility metric chosen and often we will consider the utility improvement as a percentage of the utility that can be gained

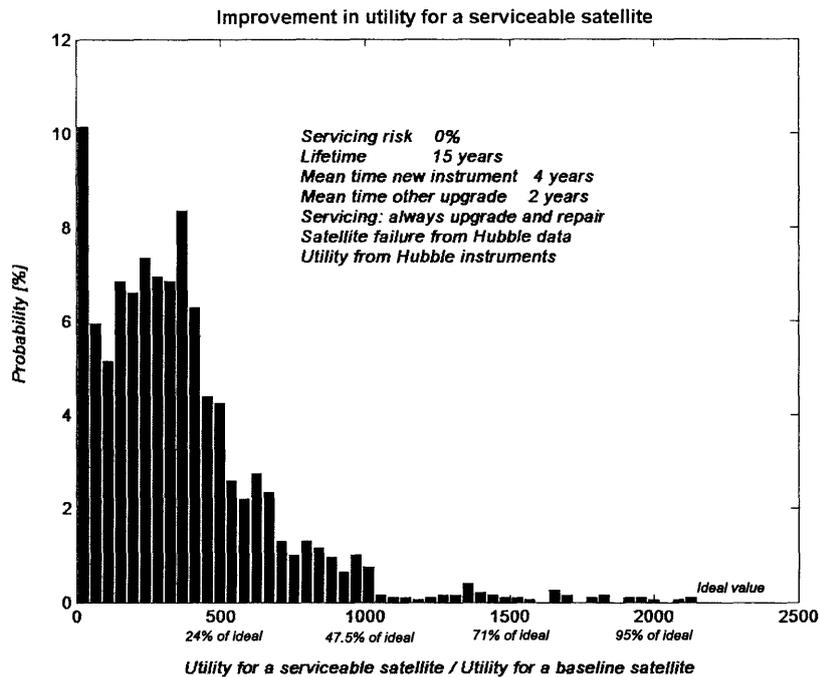
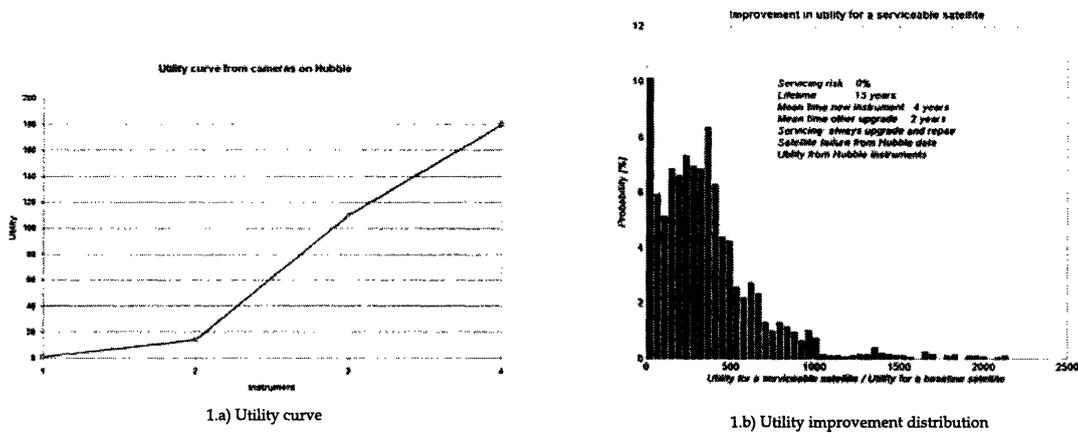


Figure 6-5: Probability distribution of the improvement in utility achieved with a serviceable satellite.

in an ideal scenario that provides the maximum utility improvement. The scale in Figure 6-5 has been rewritten in percentage of the ideal value, which is 2105 in this case. The probability to achieve a utility above 50% of the ideal is very low. Similar distributions can be generated for the total discounted mission cost and the number of servicing operations conducted over the 15-year time horizon.

Impact of the utility assumptions on the utility distribution

The shape of the utility curve used has a large impact on the distribution of the mission utility. Figure 6-6 and Figure 6-7 show the utility distributions (normalized to the utility provided by a baseline satellite) for the different utility curves described in Section 6.3.4. The distribution 1.b uses the utility curve derived from the 4 cameras installed on Hubble (NICMOS excluded). The distribution 2.b corresponds to the smooth increasing utility curve and the distribution 3.b to the S-shape utility curve. Distribution 2.b is smooth compared to distribution 3.b where a peak is seen at low utilities. In the S-shape utility curve, the utility increases significantly between the fourth and sixth innovations. The



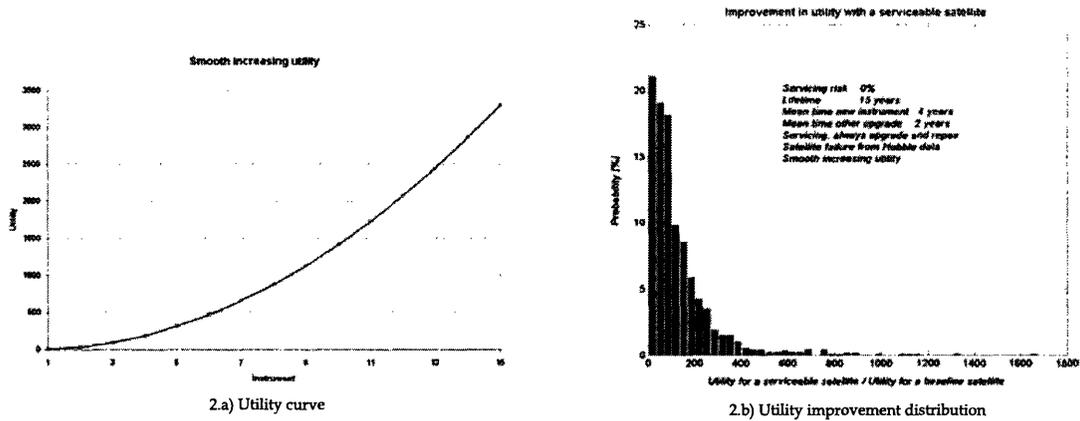
1. Utility curve from instruments installed on Hubble

Figure 6-6: Utility curve and the corresponding probability distribution of the improvement in utility achieved with a serviceable satellite for the instruments installed on the HST.

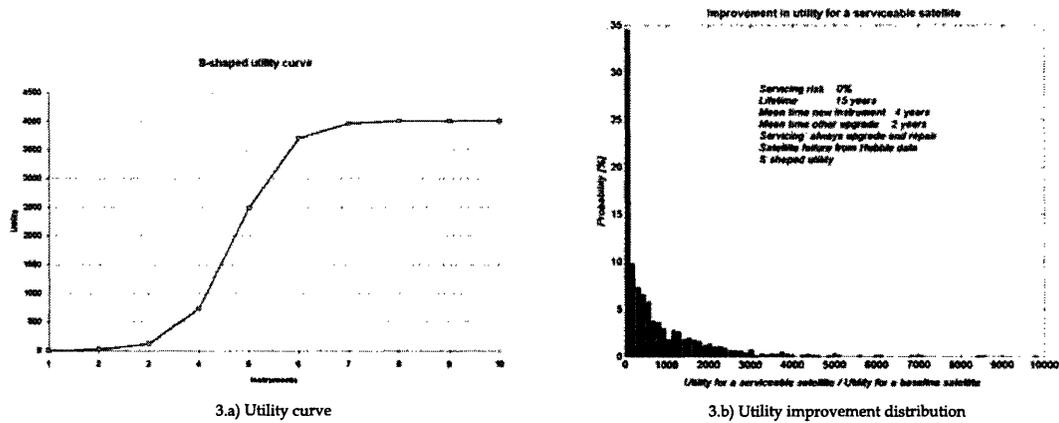
scenarios for which less than four new instruments appear are responsible for the peak at low utilities. As soon as innovation reaches the point at which utility increases rapidly with a new instrument, the total mission utility increases significantly. The assumptions about the evolution of utility has a significant effect on the shape of the distribution of mission utility, on the results and on the upgrade strategy.

Impact of servicing risk on the utility distribution

The risk of catastrophic failure of a servicing mission causes a major change of the mission utility distribution as illustrated in Figure 6-8. First, the mission utility for a serviceable satellite can be lower than the baseline utility because the mission may be lost during an upgrade mission. Therefore, on the contrary to the case of a servicing risk of 0%, the ratio of a serviceable satellite utility and a baseline satellite utility can be lower than 1. A peak at low mission utility values appears corresponding to scenarios for which the satellite is lost at some point in time during the time horizon. The probability distribution is flattened over the high utility values. For example, a 10% servicing risk causes the probability of multiplying the baseline utility by 500 to decrease from 4% to 2.5%.



2. Smooth increasing utility curve



3. S-shaped utility curve

Figure 6-7: Different utility curves and the corresponding probability distributions of the improvement in utility achieved with a serviceable satellite for the two utility curves chosen for the study.

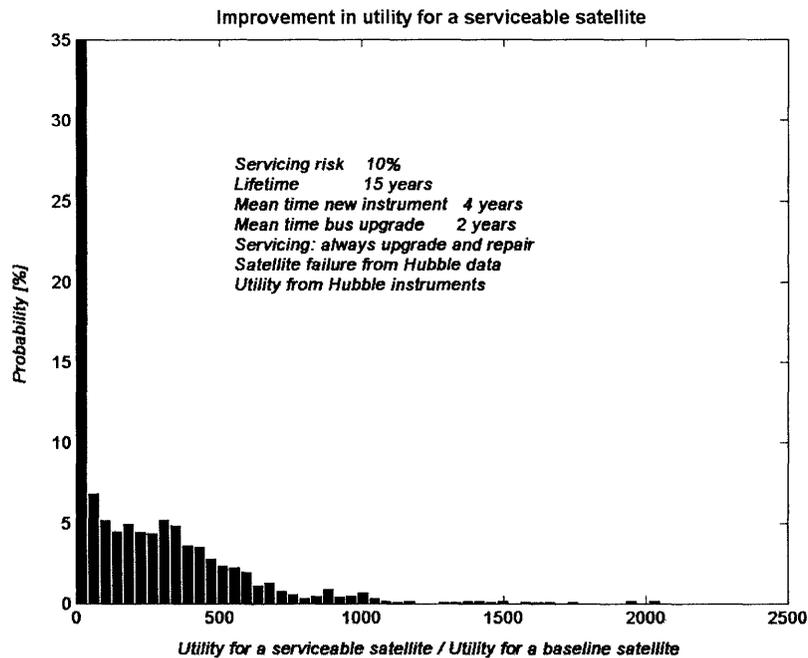


Figure 6-8: Probability distribution of the improvement in utility achieved with a serviceable satellite assuming a 10% servicing risk.

6.4.2 Satellite repair

The Hubble Space Telescope has been designed to be regularly serviced by the Shuttle. The reliability of the satellite drops below 50% after four years of operation if no repair is undergone. The implications of the design choices made for the Hubble Space Telescope and the value of the opportunity to repair are studied.

Impact of satellite failure on the baseline architecture

The utility distribution for a baseline satellite that cannot be repaired is shown in Figure 6-9. It can be seen that the mean time for a satellite failure is 3.5 years, which means that because of the choices in the design of the Hubble Space Telescope, a repair mission must be carried out on average every 3.5 years to maintain the scientific platform. Each peak in the distribution corresponds to one additional year of operation of the satellite. In all the scenarios tested, the satellite never survives more than 8 years.

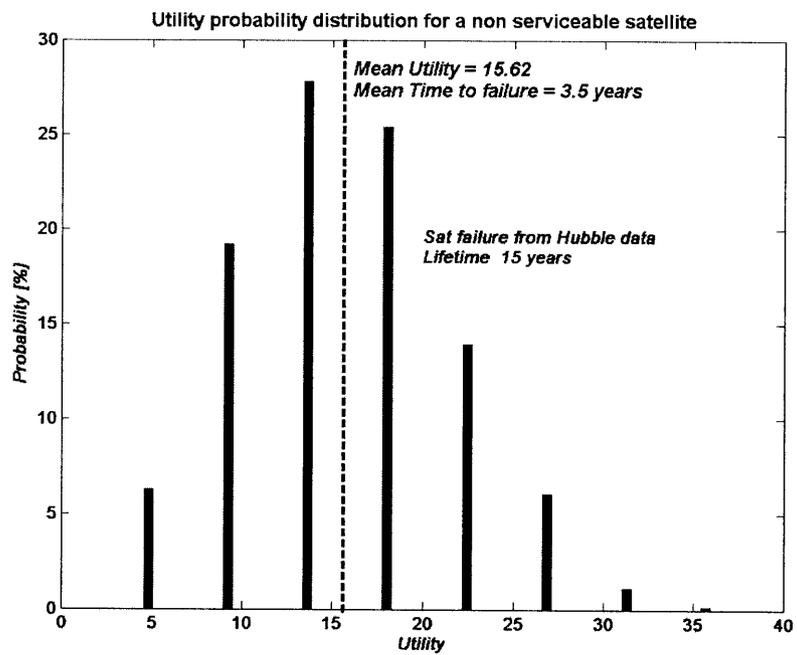


Figure 6-9: Probability distribution of the mission utility achieved with a non serviceable satellite. The probability of failure of the spacecraft is derived from the reliability of the Hubble Space Telescope.

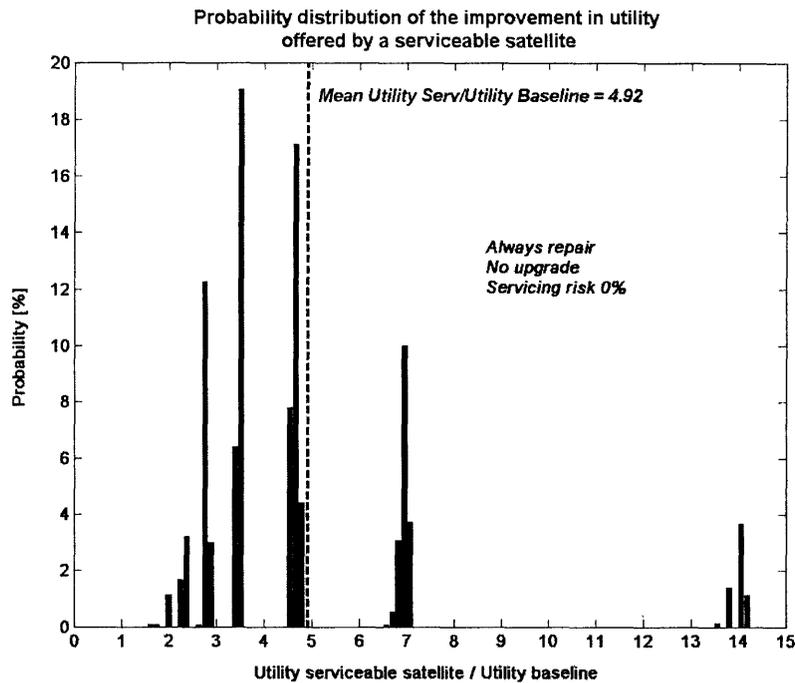


Figure 6-10: Probability distribution of the improvement in utility offered by the option to repair. The probability of failure of the spacecraft is derived from the reliability of the Hubble Space Telescope.

Using on-orbit servicing for satellite repair

The value of repairing the satellite (on-demand and scheduled repairs) can be investigated independently from the upgrade option. The mission utility distribution for a serviceable satellite is shown in Figure 6-10, assuming that the satellite is always repaired but never upgraded. The distribution is discontinuous, with each peak corresponding to a different time at which the satellite first fails. On average, the utility gained over the mission is almost multiplied by 5 when the satellite is regularly repaired. It can be noted that repairing the satellite always increases the mission utility compared to the baseline case because the satellite never survives the 15-year lifetime based on the design choices made if no repair mission is launched. The corresponding distributions of the total mission cost and the number of repair missions carried out are shown respectively in Figure 6-11 and in Figure 6-12. Approximately 4 repair missions are required on average throughout the satellite lifetime to maintain an operational platform, which corresponds to an average total cost of \$2.54 billion. The design choices that defined the spacecraft reliability curve

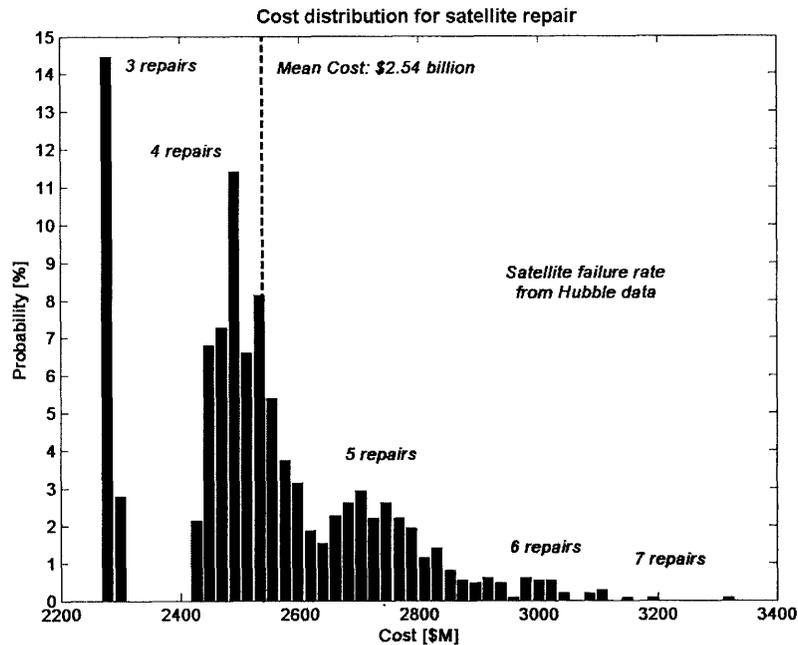


Figure 6-11: Probability distribution of the average total mission cost when the spacecraft is regularly repaired.

committed the space operator to an average of 4 repair missions and an additional cost of \$1.54 billion over the IOC cost. Across the different scenarios, a minimum of 3 and a maximum of 7 repair missions are carried out. Different peaks can be distinguished in the cost distribution corresponding to different numbers of repair missions. The peaks are clearly identifiable because the cost of a servicing mission is large. The spread of each peak is due to differences in the time at which the failures occur. Because costs are discounted, a repair mission launched later in time is considered less expensive.

Impact of servicing risk on the option to repair

The same results are presented when a 10% risk of catastrophic failure during a repair mission is assumed. The distributions of mission utility, total mission cost and the number of repair missions are shown respectively in Figure 6-13, Figure 6-14 and Figure 6-15. The utility generated over the satellite lifetime is on average four times higher than the baseline utility. However, it must be noted that there is a probability of about 8% to get a utility lower than without repairing the satellite. An average of 3.4 repair missions are carried

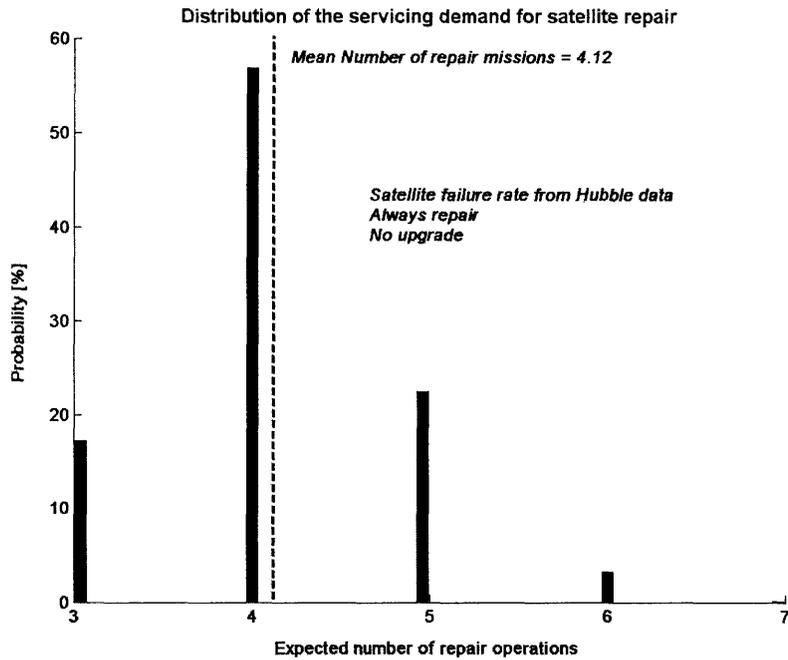


Figure 6-12: Probability distribution of the demand for satellite repair assuming a 0% servicing risk.

out corresponding to an average mission cost of \$2.3 billion. In this case, the serviceable satellite is assumed to be always repaired if necessary. Therefore, the difference in the average number of repair missions is only due to the fact that some repair missions are not demanded because the satellite is lost in a previous servicing operation. However, if the metric threshold for repair is low enough, increasing servicing risk will have a second effect on the demand for repair missions by lowering the expected utility. Some repair missions will not be launched because the space operator considers that the cost of the servicing mission is not offset by the expected utility to be gained.

6.4.3 Satellite upgrade and instrument technology evolution

The value of technology upgrade is studied independently from satellite repair by considering a 100% reliable spacecraft. The satellite is assumed to be upgraded as soon as a new instrument or a new bus technology appears. The impact of the pace at which new instruments and new payload capabilities appear is investigated.

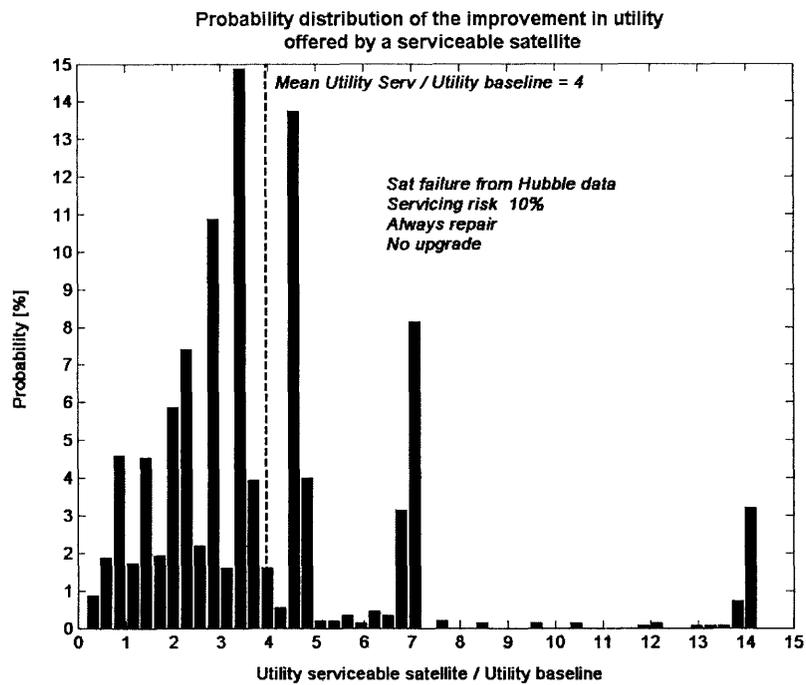


Figure 6-13: Probability distribution of the improvement in utility offered by the option to repair. The probability of failure of the spacecraft is derived from the reliability of the Hubble Space Telescope. A servicing risk of 10% is assumed.

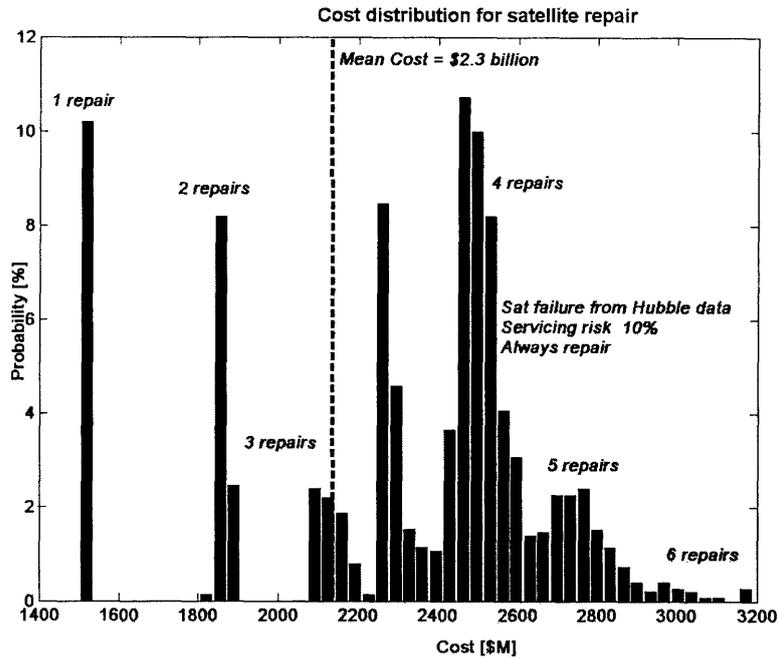


Figure 6-14: Probability distribution of the average total mission cost when the spacecraft is regularly repaired.

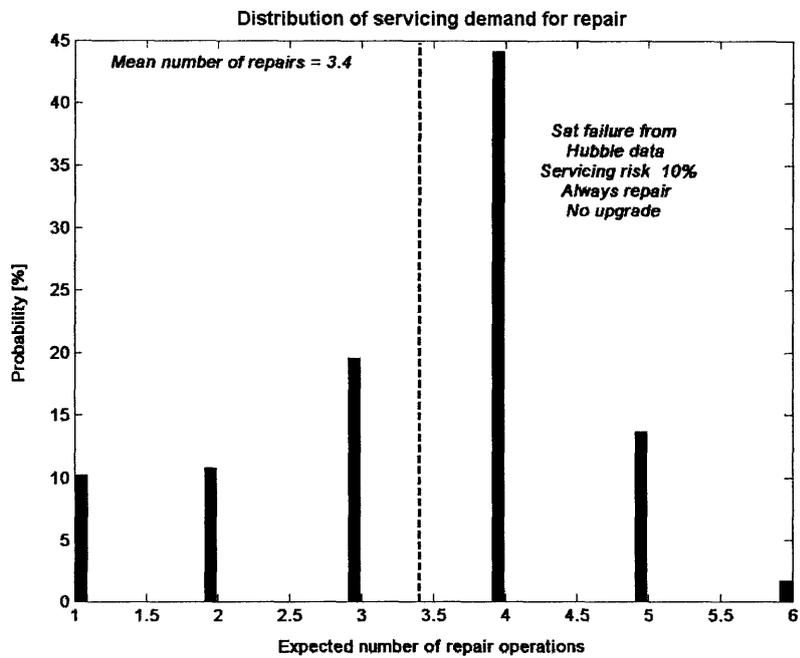


Figure 6-15: Probability distribution of the demand for satellite repair assuming a 10% servicing risk.

Impact of the mean time between appearance of new instruments

The distribution of the utility that can be expected from a serviceable satellite is shown in Figure 6-16 depending on the mean time between arrival of new instruments, assuming that an upgrade mission can be offered with a 0% risk of catastrophic failure. Utility values are normalized to the baseline utility and are represented as a percentage of the ideal value. Different reference utility levels are defined. The curves in Figure 6-16 represent the probability of getting a utility below each of the utility reference levels chosen. The figure can be understood as a map showing the probability of getting a utility within certain predefined ranges. Since there is no risk of failure during a servicing mission, the utility gained with a serviceable satellite is always higher than the baseline utility. At one extreme, if a new instrument is available every year on average, the space operator is assured to significantly improve the scientific return of the mission by getting at least 50% of the maximum utility improvement. As the time between new instrument arrivals increases, the potential improvement in utility decreases. The probability of being in the lowest range (at most 2% of ideal utility improvement) increases from 0% when a new instrument is available every year on average to 65% when a new instrument is available every 15 years on average. The value of technology upgrade increases as the pace at which technology evolves increases. Therefore, fast evolving technologies such as computer hardware are very promising candidates for satellite upgrade.

Impact of servicing risk

Figure 6-17 shows the same utility map as Figure 6-16 for a servicing risk of 10%. The probability of decreasing mission utility by regularly upgrading the satellite is significant. For a mean time of arrival between new instruments of 1 year, there is a 20% probability of decreasing mission utility by servicing the satellite. As the mean time between innovations increases, the probability of decreasing mission utility with a serviceable satellite decreases. In this case, the decision maker upgrades the satellite as soon as a new instrument appears. The faster is the pace of innovation, the more servicing missions are attempted and therefore the probability of a servicing failure over the satellite lifetime increases. Two trends can be noted in the utility map. At low mean times between innovations, the distribution shifts towards higher levels of utility as the mean time between arrival of new instruments

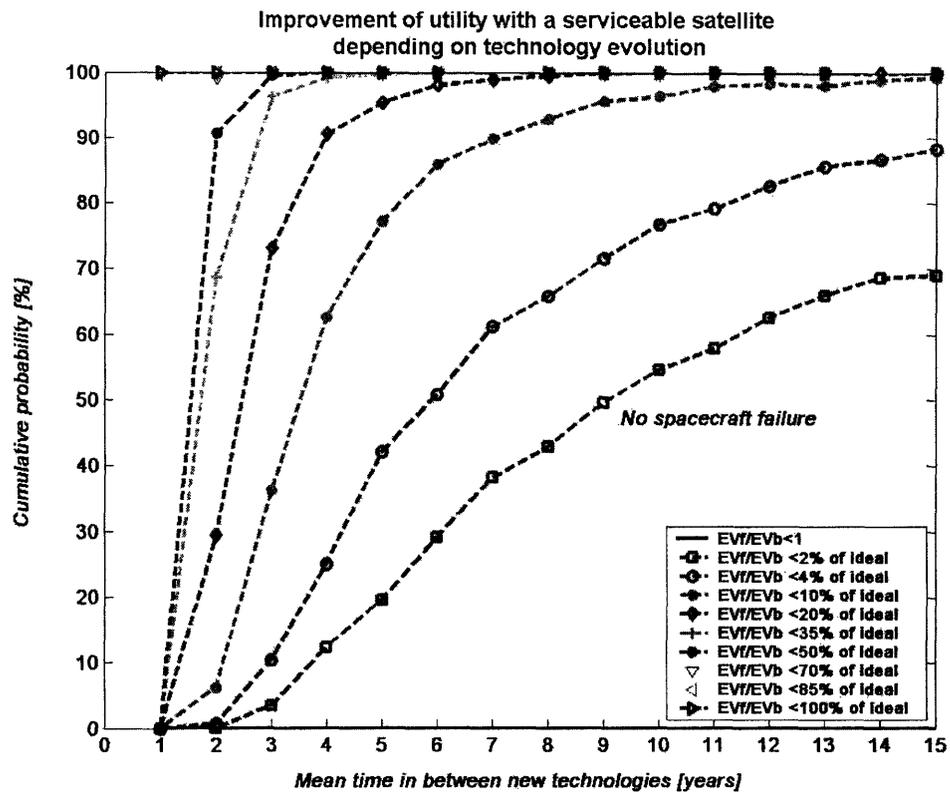


Figure 6-16: Probability distribution of the utility offered by a serviceable satellite assuming a 0% servicing risk.

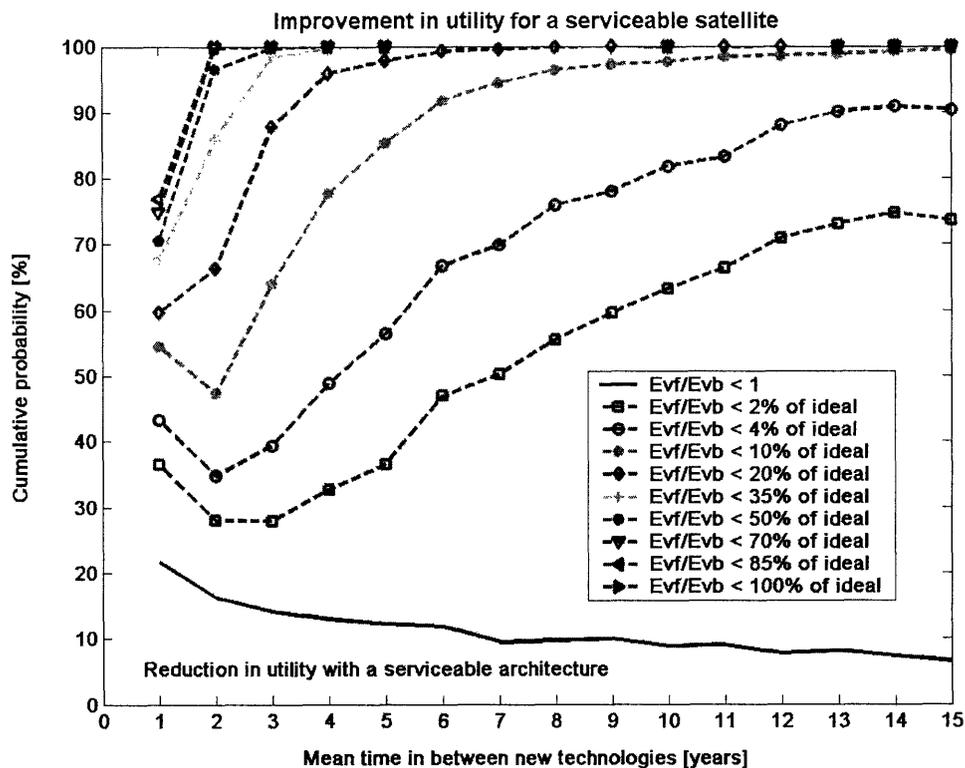


Figure 6-17: Probability distribution of the utility offered by a serviceable satellite assuming a 10% servicing risk.

increases. At higher value of the mean time between innovations, the reverse effect is seen. This results from the interaction of two competing effects. If technology evolves faster, more instruments are available and therefore more upgrade missions are launched. This translates to potentially higher mission utilities because more capable instruments are installed on-board. However, this also increases the risk of a servicing failure causing the loss of the satellite and decreasing the mission utility. With these two effects, a maximum utility is obtained when a new instrument is invented every 2 to 3 years on average.

6.4.4 Upgrade decision model

In the results shown in the previous section, the satellite is upgraded as soon as a new technology appears without taking into consideration the cost of the upgrade. The impact of the upgrade metric threshold is investigated, assuming a 100% reliable satellite. No repair mission is required to maintain the spacecraft operational. The upgrade metric therefore

includes the cost of the servicing mission in addition to the cost of the upgrade. As a reference point, a metric of 0.1 per million dollars can be understood as the decision maker requiring a minimum increase in utility of 10 times the current utility to justify an expense of \$100 million. With such a metric, an upgrade mission costing approximately \$500 million is undergone for an increase in utility of at least 50 times the current utility.

The average number of upgrade missions demanded over the time horizon is shown in Figure 6-18 assuming that there is no servicing risk. The maximum and minimum demand for the servicing market are also indicated. The demand for servicing falls rapidly as the utility metric threshold increases. This is directly related to the shape of the utility curve characterizing the instruments performance. On average, 4 new instruments appear and 4 upgrade missions are conducted if the decision maker decides to always upgrade the satellite independently from the costs incurred. If a minimum of a 5 times increase in utility is required to justify an expense of \$500 million (a 0.01 threshold), the average number of upgrade missions demanded drops to 1.5 over the 15-year satellite lifetime. The decision maker waits until the performance of new instruments is high enough to justify the cost of a servicing mission. The corresponding mission cost is shown in Figure 6-19 depending on the upgrade decision model. A minimum cost of \$1.435 billion is incurred because of the IOC costs, the cost penalty to design for serviceability, the operation costs and the termination cost. A cost of \$2.7 billion on average is incurred if an upgrade is implemented as soon as the technology appears. Mission cost is directly related to the number of servicing operations carried out. The map of average utility gained and average cost incurred depending on the upgrade decision model chosen offers an interesting decision tool. Figure 6-20 shows the utility cost map corresponding to the case studied in Figure 6-18. As the upgrade metric threshold increases, the average cost and the average utility decreases. Such a map can be used by decision makers to determine an adequate utility threshold depending on total cost constraints or minimum utility levels. The point corresponding to the lowest cost and lowest mission utility represents a case for which no upgrade is performed. The first group of points offering a normalized mission utility close to 4% of ideal corresponds to the cases where one upgrade is carried out on average over the satellite lifetime. A significant increase in utility can be gained. As the upgrade metric threshold increases, the decision maker waits until a new innovation appears that offers enough capability to justify the cost of a servicing mission. Therefore the servicing operation is on average carried out

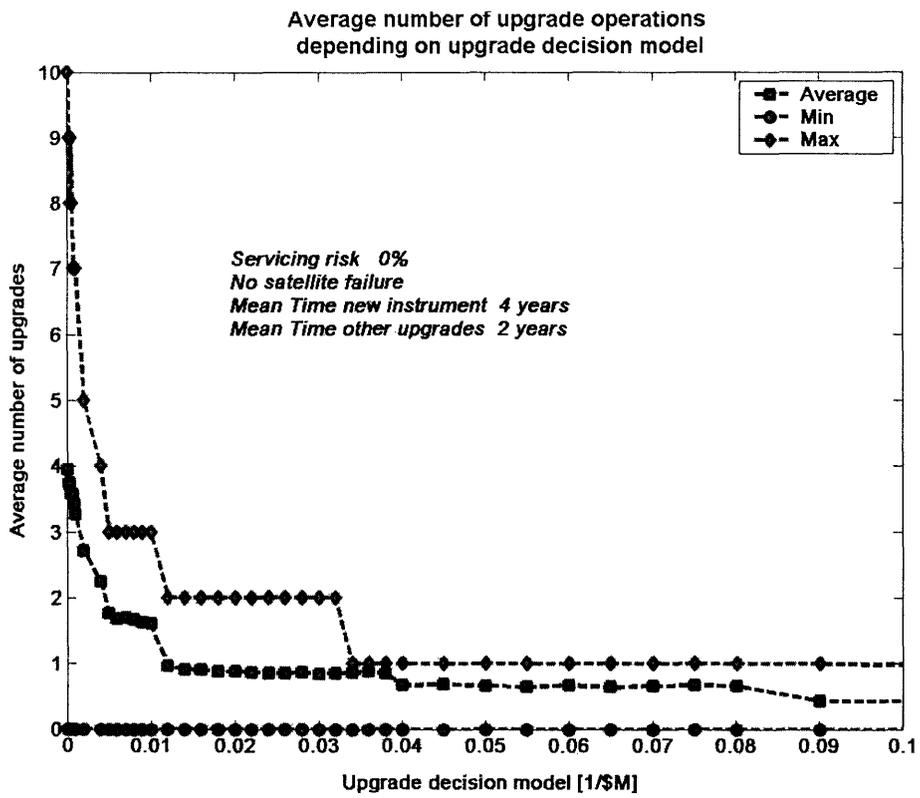


Figure 6-18: Average number of upgrades depending on the minimum metric threshold required for an upgrade.

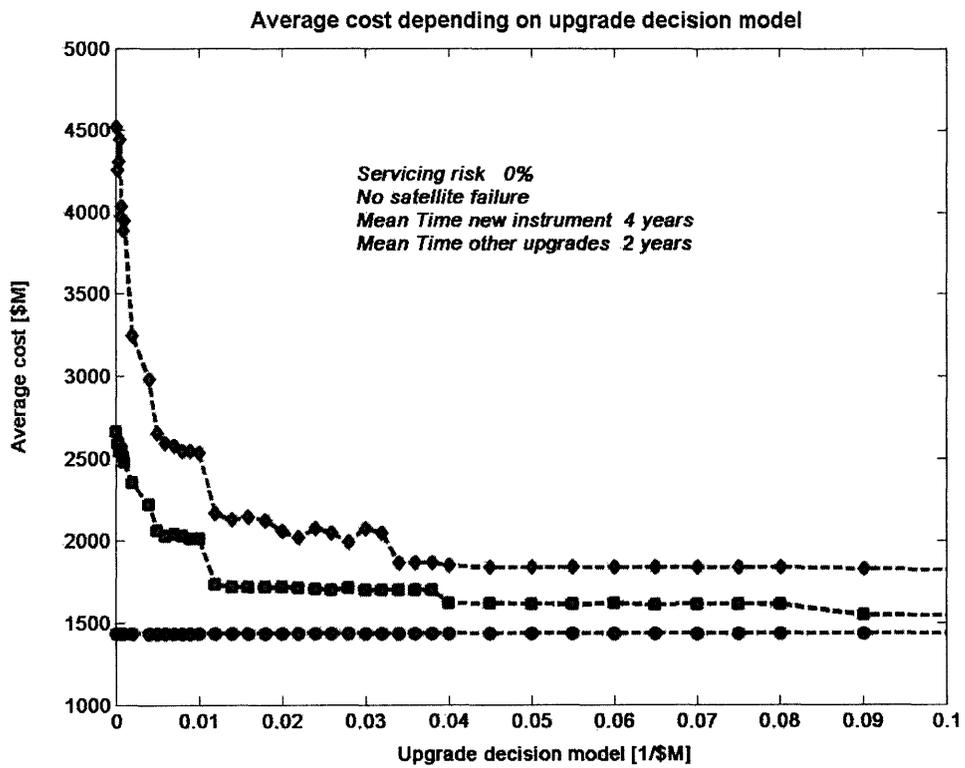


Figure 6-19: Average total mission cost depending on the minimum metric threshold required for an upgrade.

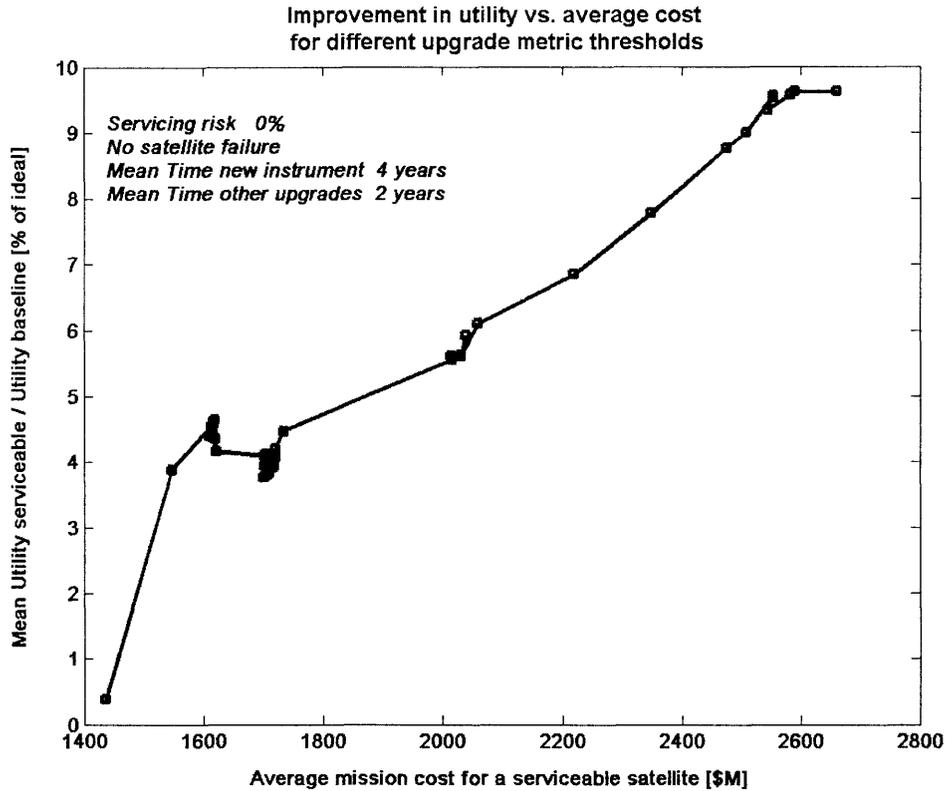


Figure 6-20: Mean mission utility and average total mission cost for different upgrade thresholds assuming a 0% servicing risk. Only upgrade missions are considered and the spacecraft is assumed to be 100% reliable.

later, which can explain the spread in the discounted costs. A more capable instrument is installed, however, it is installed later and there is a lower chance that such an instrument is ever invented, which explains the spread in mission utility. A second group of points can be seen corresponding to an average of about 1.5 upgrade missions for a total cost around \$2 billion. The same arguments can be used to explain the spread in utility: the upgrade metric threshold impacts the generation and capability of the instruments installed, the time at which the upgrade is carried out and the probability of arrival of a new instrument offering enough capability to justify the servicing mission. If the upgrade metric threshold is further increased, the average number of servicing missions demanded increases. The increase in utility and cost is large enough to see distinct points on the utility cost map. The average utility reaches a plateau when the upgrade is implemented as soon as the new technology appears.

6.4.5 Design choices: designing for serviceability or for reliability

As discussed in Section 6.4.2, because of the reliability curve of the Hubble Space Telescope, a repair mission is necessary every 3 to 4 years on average to maintain the spacecraft operational. The impact of such design choices relating to the level of redundancy or the serviceability of the satellite are explored. A trade off exists between regularly repairing the satellite in orbit and designing the satellite for a higher level of reliability. The effect of different design choices on mission utility and lifetime costs are shown in Figure 6-21. A baseline satellite refers to a non serviceable architecture (no upgrade and no repair are possible). A serviceable satellite can be repaired if deemed necessary and is always upgraded as soon as a new technology appears. Designing for reliability ensures a 100% reliable satellite but requires additional expenses in the initial satellite design. A cost penalty of 200% is shown as an upper limit and a cost penalty of 150% as an intermediate value. In Figure 6-21, the mean utility is normalized to the average utility offered by a baseline redundant satellite.

Let's first consider the architectures for which no upgrade is done. Designing for serviceability and regularly repairing the satellite is more expensive than designing for reliability even in the case of a cost penalty of 200%. Using on-orbit servicing exclusively for satellite repair does not seem viable if the cost of a servicing mission is close to the price of a Shuttle launch.

When considering the option to upgrade, two alternatives may be chosen: 1) the satellite can be designed for a high reliability and servicing missions are exclusively used to install technology upgrades or 2) the satellite can be designed to be regularly repaired and upgraded. Using on-orbit servicing for satellite repair and upgrade appears slightly more expensive than designing a reliable satellite in the case of a cost penalty of 150%. The difference in cost is not as high as when no upgrade is performed: the major cost is the price of a servicer operation and both a satellite repair and upgrade can be performed during a single servicer flight. A reliable satellite offers a slightly higher utility because of the downtime if a failure occurs.

Designing for serviceability exclusively for satellite repair does not seem a viable design choice with such an expensive servicing cost. If servicing missions are demanded to upgrade the satellite, repairs can be conducted at the same time for a small increase in cost since the

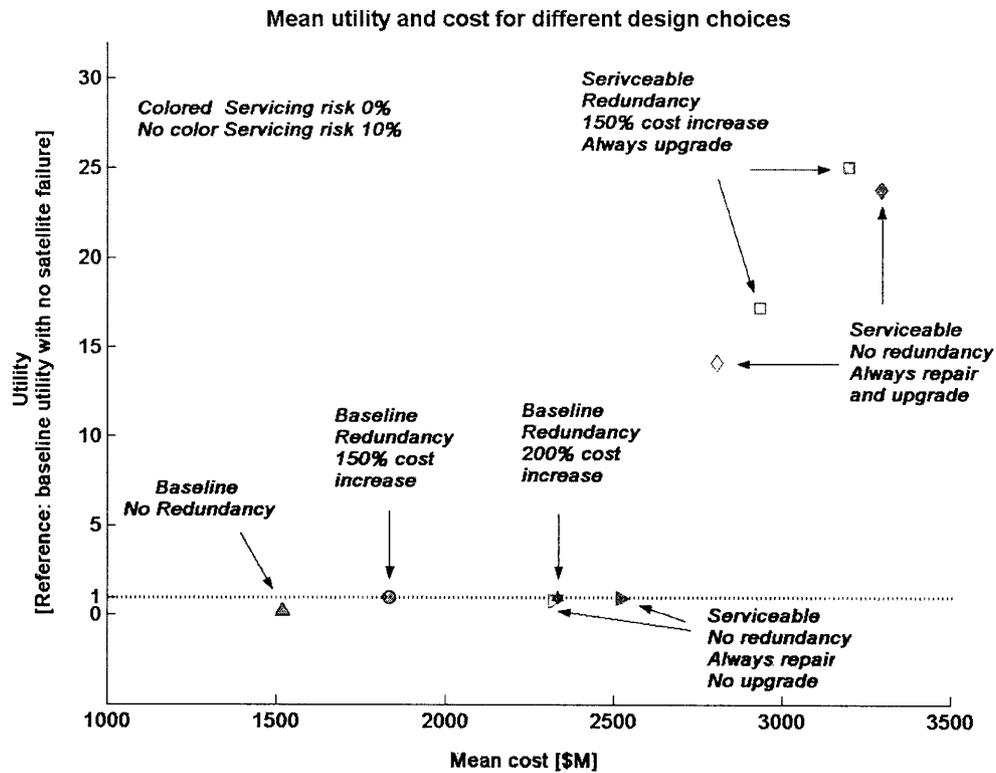


Figure 6-21: Impact of various design choices on the mission utility and total cost of the architecture.

major cost is the launch of the servicer. Critical systems could be designed for reliability while non critical subsystems or subsystems for which reliability is costly could be replaced during upgrade missions. For higher upgrade metric thresholds and if technology evolution is slower, fewer upgrade missions are demanded driving design choices towards more reliability and less reliance on serviceability. It is likely that the trade off between designing for reliability and designing for satellite on-orbit repair will be modified if the price of a servicing mission can be significantly reduced.

6.4.6 From manned to unmanned servicing missions

The previous results were based on the Hubble Space Telescope case that uses manned on-orbit servicing. The main parameters that may defer from manned to unmanned on-orbit servicing are discussed. In particular, the impact of servicing cost and servicing risk on the mission cost and utility are investigated.

Designing for serviceability The satellite must be designed to be serviced for both manned and robotic servicing operations. Astronauts have a limited mobility in space and the modules must be designed to limit the number of operations and simplify access and maneuverability of the components. It is considered that the design for robotic servicing operations would not be radically different from what is currently done for astronauts. One of the best ways to design subsystems for extravehicular activities is to make them compatible with robotic operations [8]. The cost penalty for designing a satellite for manned and unmanned serviceability should not be radically different.

Scope of the servicing operation One of the main differences between manned and unmanned operations is believed to be the degree of flexibility that can be achieved. Robotic missions are efficient for operations that are planned in advance and for which the satellite has been designed for. However, if a failure or a problem occurs that has not been thought of in advance, it will be difficult for a robotic servicer to accomplish the operation. Humans can adapt to the situation and improvise. Some unplanned operations have been carried out by astronauts on the Hubble Space Telescope, such as the repair of a power unit box that was not initially designed to be serviced. The present model could be adapted to differentiate between subsystems that can and cannot be repaired by a robotic servicer, assigning a different probability of failure for each category.

Servicing risk and cost One of the main reasons why the on-orbit servicing community examines the development of an unmanned infrastructure is to reduce the cost of servicing to make it affordable for most space missions. The development of a large demand for on-orbit servicing requires the cost of a servicing mission to be significantly lower than the cost of a Shuttle flight. As far as servicing risk is concerned, it can be argued that manned operations may reduce the risk of a catastrophic failure during the servicing operation.

The impact of servicing risk and servicing cost on the demand for on-orbit servicing, the cost of the mission and the utility gained over the satellite lifetime are studied in more details. The decision model chosen for the study requires a minimum utility of 22 to justify a repair expense of \$100 million and an upgraded utility of at least 1.2 times the current utility to justify an upgrade expense of \$100 million.

The demand curve for a servicing market depending on the characteristics of the on-orbit

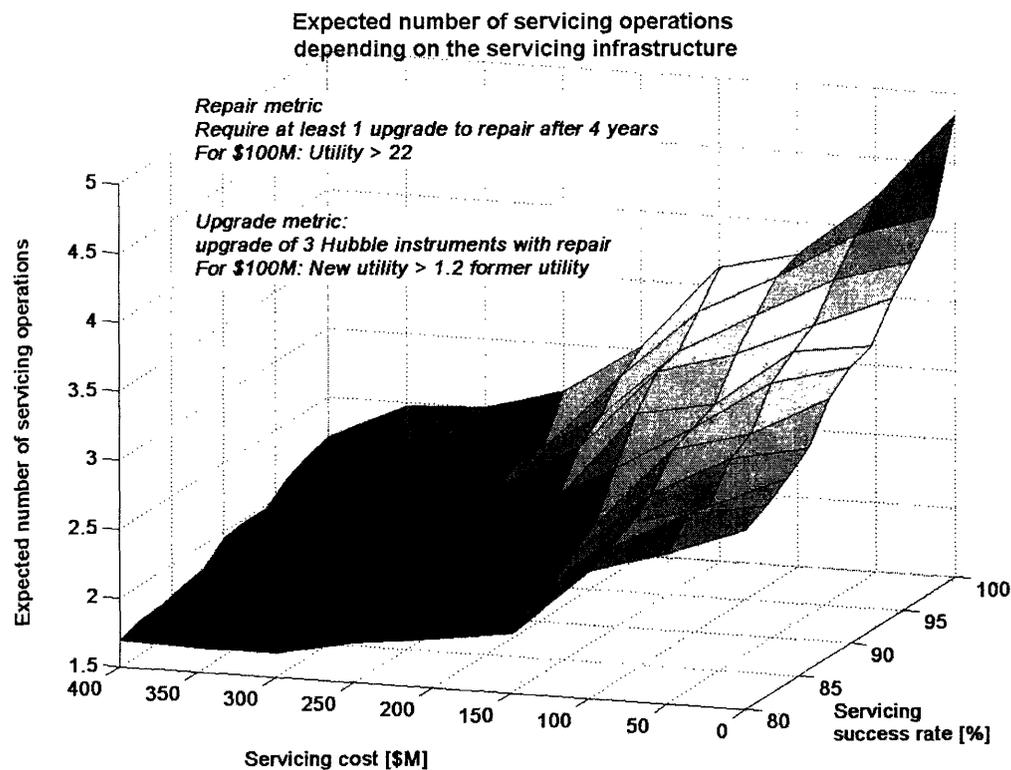


Figure 6-22: Average number of servicing operations demanded depending on the servicing infrastructure characteristics.

servicing infrastructure is shown in Figure 6-22. The highest demand is seen with a 0% servicing risk and a \$0 million servicing cost and corresponds to an average of 5 servicing missions over the 15-year lifetime. Servicing risk has a larger impact at low servicing costs because more servicing missions are demanded up to the point of a failure. The cost of servicing has a much lower impact on demand at high servicing costs. At these high values of servicing cost, an increase in the cost of a servicing operation does not modify so much the number of upgrades as the generation of the instrument installed during the upgrade. The average cost of the mission is shown in Figure 6-23 depending on the servicing infrastructure. The same trends identified in the evolution of the demand for a servicing market can be seen in the evolution of mission cost. The average cost decreases with increasing servicing risk as the demand for servicing decreases. The average cost increases with increasing servicing cost and the rate of increase is higher at low values of servicing cost. The mission cost is more sensitive to servicing cost than servicing risk. Servicing risk only affects the

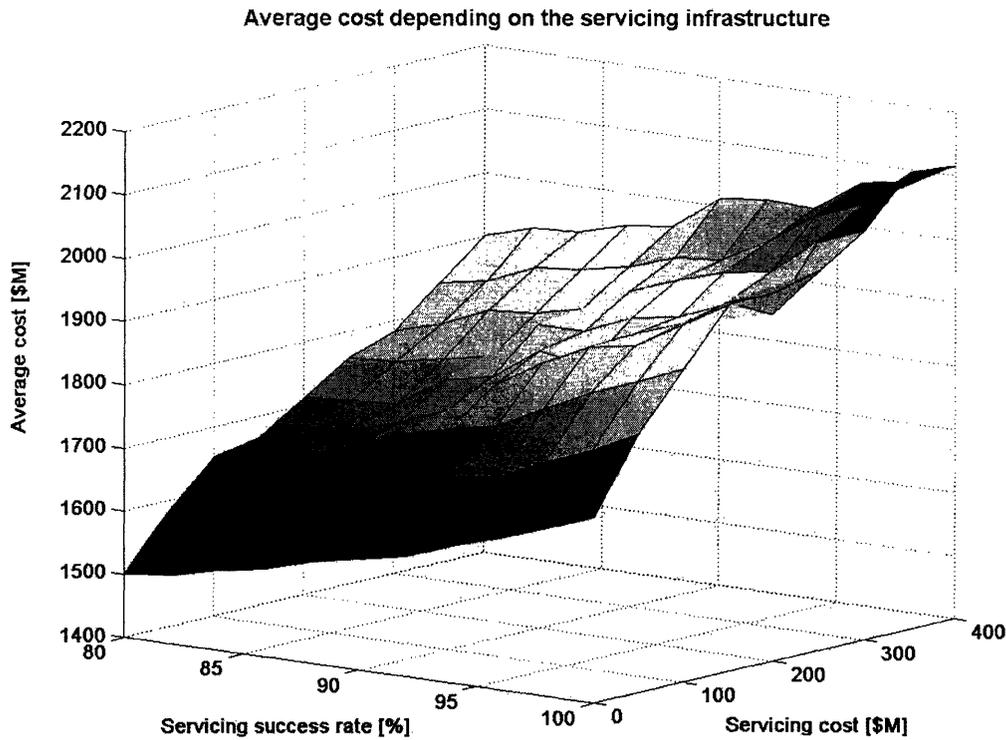


Figure 6-23: Average total mission cost depending on the servicing infrastructure characteristics.

demand for servicing while servicing cost has an impact on both demand and the price paid. Figure 6-24 illustrates the corresponding evolution of mission utility and cost depending on the servicing infrastructure characteristics. Utility is normalized to the baseline utility. Servicing risk significantly reduces the mission utility. A 10% risk causes the mean utility to drop from 45% of ideal to 30% of ideal. The impact of servicing cost appears different at low and high servicing costs. At low servicing costs, utility is more sensitive to an increase in servicing risk than in servicing cost. At high servicing costs, utility decreases rapidly as the cost of a servicing operation increases. At low costs of servicing, up to \$100 million, the first new instruments are installed as soon as they appear providing a high utility. As the cost of servicing increases within this low range, the last upgrades are cancelled but the first upgrades are still carried out. The last instruments that are cancelled, are those that were operating for a shorter period and for which the probability of appearance was lower. Therefore the drop in utility is small because the first upgrades are assured. If the cost

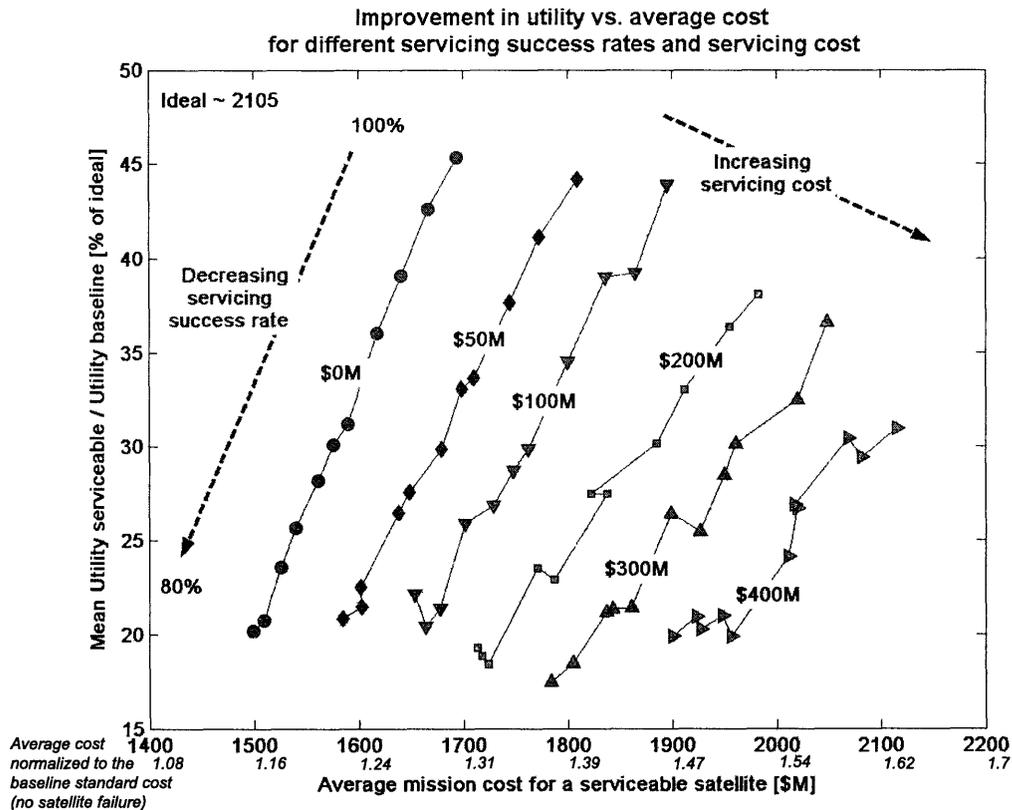


Figure 6-24: Impact of servicing risk and servicing cost on the mission cost and utility of the serviceable architecture.

of servicing is high, above \$200 million in this case, only one or two upgrade missions are carried out. As the cost of servicing increases within this high range, the space operator has to wait until a more capable instrument appears that offers enough capability to justify the high servicing cost. At high servicing costs, the first upgrades that occur early on in the mission and that are the most probable to appear are not performed. Therefore, the loss in utility due to an increase in servicing cost is larger.

6.5 Limitations of the model

The model could be improved by more closely modelling the Hubble Space Telescope. In particular, more than one payload slot could be considered and instruments other than cameras could contribute to the scientific return. The effect of complementary instruments on utility could be added to account for the increase in utility when a target can be studied with different types of instruments. The impact of bus upgrades can be refined by having

a technical estimate of the impact of the upgrade. The degradation of the instrument performance with the time of operation is not included and can be of importance in the decision to upgrade. Finally, the increase in performance promised by the new technology could be uncertain and could be added as a source of uncertainty into the Monte Carlo simulation.

6.6 Conclusion

The value of implementing new payload instruments and bus subsystems technologies on a scientific mission has been studied, based on the example of the Hubble Space Telescope. Designing for serviceability exclusively to have the option to repair the satellite does not seem very valuable for servicing costs similar to the cost of a Shuttle mission. Designing a more reliable satellite may be a more secure and cheaper solution to ensure an operational satellite.

On the contrary, upgrading can significantly increase mission utility especially if the technology embedded in the serviceable modules is evolving rapidly. If there is a risk of catastrophic failure during a servicing operation, a trade off appears between the desire to upgrade more often to achieve a higher utility and the increased risk of losing the mission as the number of servicing operations increases. Different upgrade strategies can be tested to help space designers and operators decide on the best strategy to follow depending on cost and minimum utility constraints.

Technology upgrades via on-orbit servicing have been identified as a very promising concept in this case. Large increases in mission utility can be realized for a cost significantly lower than the cost of replacing the whole satellite. On-orbit servicing is very attractive in this example because large increases in mission utility can be gained by upgrading and because there is no other alternative that can provide a similar increase in utility for a lower cost and risk level.

Chapter 7

Policy enablers and barriers to the development of on-orbit servicing

On-orbit servicing offers a new paradigm in space systems, changing the way satellites are designed and operated. International Space and Technology, Inc., a new company working on the development of a space tug remotely commanded by humans from Earth, proposes the following example to highlight the radical shift in perspective proposed by on-orbit servicing [38]:

“Imagine what would happen if you were driving your \$20,000 car down the road and you ran out of gas or blew a tire. But the problem is, there are no tow trucks, no gas stations, no roadside assistance, no spare tires (they haven’t been invented yet). Well, that would pretty much render your car useless, just a piece of roadside art, and you’d have to buy another car (with four new tires and a tank full of gas). That would be a pretty expensive proposition. Seems far-fetched, but that’s exactly the situation for satellites today. [...] Simply put, IST [International Space and Technology, Inc.] could be to satellites what AAA is to cars.”

Space systems are one of the few complex and expensive systems that do not benefit from a maintenance infrastructure. If on-orbit servicing has been discussed and studied for a long time, no on-orbit servicing infrastructure has been developed yet. Technical challenges are not believed to be the only hurdles to the development of an on-orbit maintenance infrastructure for satellites. The space community is largely divided on the issue of on-orbit

servicing, with two opposed camps often referred to as the “Yes camp” and the “No camp”. In this chapter, the potential policy barriers and enablers to the development of a market for on-orbit servicing are explored. First, the interests of the different stakeholders involved are investigated. Some of the main barriers to the development of on-orbit servicing are then presented before discussing some potential policies to promote on-orbit servicing. Finally, some policy issues related to the operation of on-orbit servicing are explored.

7.1 Stakeholders

The main stakeholders involved in the debate over on-orbit servicing can be divided in the following categories [3]:

- Space systems users: commercial, scientific and military
- Space operators
- Insurance companies
- Space manufacturers
- Launch providers
- Potential on-orbit servicing providers
- Government and international bodies
- Space agencies

7.1.1 Main beneficiaries

The end users as well as the space operators would greatly benefit from the development of on-orbit servicing. As discussed in previous chapters, they could benefit from the flexibility offered by on-orbit servicing, both as an insurance in case of a component failure and as a way to take advantage of new opportunities. Military users have shown a particular interest in on-orbit servicing. Insurance companies are also in favor of a maintenance infrastructure for satellites in orbit. On-orbit failures are responsible for almost half of the insurance claims, that correspond to about \$500 million per year on average between 1997 and 2001 [12]. A simple on-orbit inspection of failed satellites could be very useful for insurance

companies. The causes of the failure could be better known and potential solutions could be determined to restore the satellite performance. The lessons learned from the inspection could be used as feedback for space manufacturers to improve production. Satellite repair and tugging offer alternatives to the expensive replacement of failed satellites. The risk for insurance companies could be significantly reduced, leading to lower insurance claims and payments. The demand for on-orbit servicing from this group is closely related to the risk and cost of a servicing operation.

7.1.2 Contributors to the supply of on-orbit servicing

Space manufacturers, launch providers and on-orbit servicing providers will be key to providing a maintenance service for satellites in orbit. Satellite manufacturers are responsible for the design of the satellites. The design modifications required to make satellites accessible and serviceable by robotic servicers will directly impact space manufacturers. On-orbit servicing providers will ensure the link between customers, space manufacturers and the launch companies and will be managing the operation of the servicing infrastructure elements. Launch companies are key to providing a cheap and responsive access to space for servicers. The servicing cost, risk and the responsiveness of on-orbit servicing depend largely on launch opportunities. Space manufacturers and the launch community have conflicting interests concerning on-orbit servicing.

Launch companies The impact of on-orbit servicing on the demand for space launches is not clear. The operations of the servicers would create new market opportunities for launchers. On-orbit servicing could also increase the demand for space activities by reducing the cost of space systems. However, the repair and upgrade of satellites in orbit will decrease the number of replacement satellites launched after a failure or against technology obsolescence. The net effect on the demand for launches is difficult to predict. Moreover, it can be noted that the trend in the launcher industry has been towards vehicles capable of delivering larger masses to orbit, following the trend towards larger and heavier satellites. The servicers will be smaller spacecrafts and on-orbit servicing providers would be more interested in frequency than mass to orbit. Therefore, it is possible that the current strategy of some major launch providers will not be aligned with the needs for the new servicer launch market.

Space manufacturers Similarly, space manufacturers are potentially interested in the development of on-orbit servicing as a way to create new market opportunities. The design of the robotic servicers and other elements of the servicing infrastructure could create a new demand in a highly competitive industry characterized by overcapacity. However, manufacturers have reasons to resist the development of on-orbit servicing. First, the repair and upgrade of satellites in orbit will decrease the need for new satellites. Similarly to the case of the launch market demand, the net effect of on-orbit servicing on the market for space manufacturers is not clear. Second, designing for serviceability will cause major modifications in the design process and will require a main shift in the designers' culture. Major design choices are often made based on experience and people are likely to resist such a radical shift in the concept of satellite design. Technical modifications will be necessary to adopt a modular design. Designers will also need to rethink the way system requirements are derived. The type and scope of flexibility that should be incorporated in the initial design will be as important as the immediate performance of the satellite. Finally, space manufacturers are highly risk averse and will be reluctant to commit to on-orbit servicing before a demonstration program can prove safe on-orbit servicing operations.

7.1.3 Other stakeholders

Governments, space agencies and international bodies will have an impact on the political context and can provide resources to promote on-orbit servicing. Government and space agencies can contribute to the development of critical technologies and demonstration programs to prove the viability of on-orbit servicing. Policy decisions and regulations can create incentives towards the acceptance of on-orbit servicing and the development of a maintenance infrastructure. International bodies can also have an impact on the future of on-orbit servicing through regulations concerning global space issues such as space debris for example.

7.2 Major barriers to the acceptance of on-orbit servicing

Technical challenges are still ahead to allow space systems to be routinely maintained in orbit. However, technology is not the only hurdle to the success of on-orbit servicing. Some critical policy and economic barriers have been identified that must be overcome

before the concept of on-orbit servicing can be fully endorsed by the space community. The use of serviceable satellites will require profound changes in the way space systems are designed and operated. The risk averse space industry will likely be very reluctant to such a radically different concept and must be convinced of the large benefits offered by on-orbit servicing. Finally, one of the most critical hurdle to the development of a servicing market is a so-called “chicken and egg” problem. Satellites will not be designed for serviceability before the service can be provided, and no provider will invest in on-orbit servicing before a demand exists and satellites are designed to be serviced.

7.2.1 Organizational and cultural resistance

On-orbit servicing offers a radically different approach to the design and operation of space systems. Both designers, operators and end users will need to change their current practices to adapt to the new concept of serviceable satellites. The space community is likely to be resistant to such profound cultural and organizational changes.

A modular design The initial design of the satellite determines the degree of adaptability of the system and drives the scope of the flexibility offered to the end user. First, the robotic servicer must have access to the satellite subsystems. Designers will also likely need to rethink the traditional functional subsystem boundaries. In a serviceable satellite, the function performed by the module is not the only characteristic that should be considered in choosing the module boundaries. Other critical parameters to consider may be whether the user will want to modify the system over the satellite lifetime, the failure rate of the components, the pace at which the module technology evolves and the complexity of the interfaces. Components that are likely to be changed often and components that are likely not to be modified may not be incorporated in the same module. The modules will be designed to simplify interfaces so that modules can be easily switched and replacement units easily installed. Such considerations are not necessarily given the priority in current satellite design processes since the satellite is not aimed at being modified. Therefore, going from a complex non flexible system towards a modular, potentially evolving architecture requires a complete review of design processes. Satellite designers are often relying on experience and many design choices are heritage from past designs. A major shift in the culture of space designers is necessary to enable the development of on-orbit servicing. Such

design changes will also lead to changes in production and assembly.

Reliability and redundancy Satellites are very expensive assets and therefore, designers are largely focusing on ensuring a high system reliability. There is a culture of high reliability and a tradition of using highly reliable components, expensive space hardened systems and adding redundancy in space systems. Designers would need to adopt a different mindset and to consider the trade off between the cost of high reliability and the cost of repairing the satellite in orbit.

Requirements and system architecture The conceptual phase of a serviceable satellite will also be radically different. The satellite should not be considered as a point design offering a certain capacity over its lifetime but as a stage on a set of possible evolution paths. The satellite requirements determine the evolutions that are possible and the one that are discarded. The desirable degree of flexibility should be determined in close relation with the end user.

Organizational and structure changes The cultural changes highlighted in the previous paragraphs will likely need to be reflected in changes in the structure and organization of design teams. In particular, experts on different traditional subsystems will need to work in close collaboration and overcome potential tensions between different disciplines. In current satellite design, different teams are specialized in the optimization of particular functional subsystems such as the power, thermal or communication subsystems. Common boundaries in design teams must be overcome to cooperate in determining the best modular design for serviceability and managing the complex interfaces in the modular architecture.

Satellite operation End user and space operators may also need to change their approach to satellite operation. On-orbit servicing offers new opportunities for the management of a satellite fleet. A more strategic approach should be adopted considering potential servicing operations as an alternative to current options. In addition to monitoring the health of the satellite, satellite users and space operators must decide on the potential upgrade or modification of the system depending on the evolution of the satellite environment. New concepts could even be considered with the emergence of a routine maintenance infrastructure. We could imagine individual satellites being replaced by space platforms offering

slot leases to users. Payloads would be replaced regularly at the end of the lease contract.

Changes in the culture and organization of an industry or a company are usually slow and difficult to implement. People are resistant to changes in their practices and the space industry is no exception. Space designers and operators rely heavily on past experience and will need to be convinced of the benefits of on-orbit servicing before endorsing this new paradigm. The risk averseness characterizing the space industry makes the organizational and cultural hurdles all the more critical.

7.2.2 Risk averse industry

The space industry is highly risk averse and therefore suspicious of any unproven concept. Many studies have been carried out to highlight the benefits of on-orbit servicing and investigate the technological challenges necessary to enable the maintenance of satellites in orbit. However, space operators often show scepticism when asked their opinion about on-orbit servicing. No demonstration program has been carried out and many people see the repair and upgrade of satellites in orbit as a fiction. The potential large benefits claimed by on-orbit servicing valuation studies do not convince a risk averse audience and risk is one of the major arguments held against on-orbit servicing. Space manufacturers and users do not consider that the benefits of on-orbit maintenance are large enough to justify the risk of losing the satellite during a docking operation. The complexity of designing for serviceability is an additional factor of risk. On-orbit servicing is judged as far more risky than other proven alternatives. The risk averseness of the space industry is a critical barrier to the acceptance of on-orbit servicing and should be addressed to ensure the emergence of this new paradigm. Detailed valuation studies emphasizing the benefits offered by on-orbit servicing and a demonstration program to prove the feasibility of safe on-orbit servicing operations seem necessary to convince the space community to participate in the development of on-orbit servicing.

7.2.3 Economic viability

The economic viability of on-orbit servicing is often questioned by private companies and investors, as commented by Nicholas Johnson, NASA's Chief Scientist and Program Manager for Orbital Debris at the Johnson Space Center in Houston [20]:

“The technology exists to support such operations, but the real issue is whether any of the concepts are economically viable”

The cost and added complexity of designing for serviceability is thought to offset the potential benefits of on-orbit servicing. The business case for on-orbit servicing is not considered to be viable. Precise and in-depth valuation studies must be carried out to determine what are the most promising applications of on-orbit servicing and to estimate the actual value of on-orbit servicing. In particular, on-orbit servicing must be evaluated in comparison to other alternatives, such as changes in the initial design, to determine the viable applications of on-orbit servicing and to potentially prove its economic viability.

7.2.4 Chicken and egg problem

As discussed previously, a satellite must be initially designed for serviceability. As a consequence, existing satellites cannot benefit from an on-orbit servicing infrastructure. This creates a “chicken and egg” problem that is a huge hurdle to the development of a market for on-orbit servicing. Investors will consider developing an on-orbit servicing infrastructure if there is a demand for such a service in the space community. The emergence of a demand for on-orbit servicing requires satellites to be designed for serviceability. However, space manufacturers and space systems users will not design modular serviceable satellites if no on-orbit servicing infrastructure is implemented to provide maintenance to satellites. This leads to a circle argument in which demand is required to justify the provider’s investment and the provider infrastructure is required to foster demand. In light of this argument, it can be seen that market forces do not seem sufficient to enable the development of on-orbit servicing and external policies are required to solve this “chicken and egg” problem.

7.2.5 Supply and demand

Two conditions seem to be required to ensure the success of on-orbit servicing. First, a demonstration program is required to prove the concept of on-orbit servicing and to develop critical technologies before a servicing infrastructure can be developed. Second, it is necessary to have a first group of satellites designed for serviceability to create an initial installed base. This initial demand will initiate profitability for the servicing market and therefore will stimulate the emergence of a provider. Studies have shown that a servicing

infrastructure requires a minimum number of target satellites to be profitable. Moreover, if this initial group of serviceable satellites is large enough, a band-wagon effect could be created. The concept of on-orbit servicing could then slowly disseminate and be adopted by the whole space community.

7.3 Private development of on-orbit servicing

In light of the policy barriers identified in the previous section, one can wonder whether market forces alone can lead to the emergence of a private on-orbit servicing infrastructure.

Private space tug efforts Some private companies have been interested in the concept of on-orbit servicing and have studied potential technical solutions for space tugging. Orbital Recovery Inc. and International Space and Technology, Inc. are two examples of such companies.

It must be noted that the interest of private investors have been focusing on applications of on-orbit servicing for which an immediate demand could emerge and for which risk was less of a concern. The technical solutions proposed by the private companies focus on servicing existing satellites so that demand can emerge without requiring modifications in the initial satellite design. The private market concentrated on the applications for which the "chicken and egg" problem identified earlier could be overcome. For example, the servicer proposed by Orbital Recovery Inc. attaches to the satellite kick apogee motor and serves as a propulsion system for the spacecraft. Moreover, private providers have first aimed at less risky missions such as the salvage of satellites launched in the wrong orbit or the life extension of GEO satellites. In these cases, the satellite is either lost or at end of life if no servicing mission is undergone. Therefore, the loss of the satellite in case of a failure of the servicing operation is less of a concern for the user.

Private investors have been interested in the concept of satellite tugging and space system life extension. The emergence of private companies offering a space tugging service is a first step towards the acceptance of on-orbit servicing and is beneficial in initiating a change in the way space systems are considered. However, it is believed that the development of a private large scale on-orbit servicing infrastructure is very unlikely.

Difficult business case for a private large on-orbit servicing infrastructure More innovative applications of on-orbit servicing that go beyond satellite tugging are more risky and will require the satellite to be designed for serviceability. Private investors are likely to be too risk averse to support such applications of on-orbit servicing, for which demand is highly uncertain and that require a major shift in the way space systems are designed and operated. Market forces will not be sufficient to overcome the barriers identified in the previous section and to lead to the development of a private infrastructure for the repair, refueling and upgrade of satellites. Existing satellites cannot be serviced and the emergence of a demand is conditional on major evolutions within the space industry. The concept of on-orbit servicing is not proven yet and the amount of capital required to develop the necessary technologies and launch a demonstration program is likely to be large. Private capital will be difficult to raise for such an uncertain project. The development of a large on-orbit servicing infrastructure will likely require some kind of government intervention.

7.4 Policies to promote on-orbit servicing

Government and international space bodies have a large role to play in the emergence of on-orbit servicing since they are responsible for the political context within which the space industry evolves. Their involvement can vary from creating incentives for private investors, to larger investments in research and technology development or to a publicly-funded on-orbit servicing infrastructure.

7.4.1 Creating incentives

Policies can be implemented to create incentives for the development of on-orbit servicing. Regulations can aim at fostering demand or at reducing the actual cost for providers. Regulations limiting the creation of space debris are likely to have an impact on the emergence of on-orbit servicing. The amount of non-operational objects in space is growing rapidly and the risk of a collision with operational satellites has been a growing concern in the space community. Discussions have been carried out to decide on what policies should be implemented to limit the creation of space debris. Repairing and refueling satellites could offer a solution to reduce the number of dead satellites in orbit. Governments could also implement tax incentives to promote the design and operation of serviceable satel-

lites. Different approaches can be chosen to overcome the “chicken and egg” problem by acting on supply, demand or on both. Incentives can be aimed at fostering demand for servicing operations, assuming that once some demand exists, the servicing market will be attractive enough for private providers to invest in the development of on-orbit servicing. Incentives can also be provided to the potential on-orbit servicing providers to reduce the apparent high entry cost and uncertainty surrounding the servicing market, assuming that the demand for on-orbit servicing will emerge as soon as the service will be available.

7.4.2 Development of critical technologies

Providing a proof of the on-orbit servicing concept can be an efficient solution to overcome the natural risk averseness of the space industry and to convince the space community of the feasibility of on-orbit servicing. A government-funded demonstration program could be implemented to develop the critical technologies required for the repair, refueling and upgrade of satellites in orbit. The program should be planned with the perspective of transferring the technologies to the private sector to enable the development of a private on-orbit servicing infrastructure. The Orbital Express program supported by DARPA is an example of such a government-funded demonstration program for on-orbit servicing. The goals of the Orbital Express program is to demonstrate on-orbit rendez-vous and docking, replacement unit and fuel transfers and to develop a standard docking interface. The program has been designed to enable the transfer of critical interface technologies to the commercial world. However, the goal of the program is to develop both military and civil applications to on-orbit servicing, which may create security issues and potential divergence in the system requirements.

7.4.3 Government-funded on-orbit servicing infrastructure

The government could contribute to the acceptance of on-orbit servicing by deciding to commit to serviceability for government space systems. A policy could be implemented to design all new government space systems for serviceability, therefore creating the initial pool of target satellites to stimulate demand. And the deployment of the infrastructure would be publicly funded. The system could be privately operated and even planned to be later transferred to the private sector. Customers would only be charged the marginal cost of the servicing operation.

Intelsat and the national highway system In the United States, an analogy can be drawn with two other examples in which the US government decided to fund the development of a large project: the creation of Intelsat, an international space communication organization, and the development of the national highway system.

The creation of the International Telecommunications Satellite Consortium (Intelsat) was initiated in 1964 by the US government. The US government decided to internationalize the technology of communication satellites to “achieve a global commercial telecommunications satellite system to provide, for the benefit of mankind, the most efficient and economical facilities possible” [17]. One of the main objectives of this US policy was to enhance national prestige and to strengthen US relations with developing countries in the context of the Cold War [21].

Another example of a publicly funded large scale infrastructure is the construction of the national highway system [14]. 90% of the original cost was provided by the Federal government, the remaining 10% of the cost being born by the States. The users of the highway system only pay the marginal cost of using the system through a federal tax on fuel. The rationale to justify and gain support for this policy was that a highway system was necessary to move troops and military equipment around the country and was a question of national security. The national US highway system was therefore called the Defense highway system. Another major contributor to the success of this program is the support of all stakeholders who recognized the large potential economic spill overs that could be gained from this transportation system.

Following the model of these two examples, we will investigate if a plausible policy argumentation can be found to justify a government intervention in the development of on-orbit servicing. Two policy arguments are analyzed: on-orbit servicing for national security purposes and on-orbit servicing as a way to ensure a sustainable space industry.

On-orbit servicing for military use As for the highway system, a policy argument could be constructed around national security and the necessity of on-orbit servicing for military applications:

All military satellites should be designed for serviceability and an on-orbit servicing infrastructure should be developed to repair, refuel and upgrade military

satellites for national security purposes.

It is believed that this strategy could generate enough support to be successful for two main reasons.

On-orbit servicing first offers very promising applications for military space systems. Availability is a critical requirement for military space assets and on-orbit servicing could offer a way to quickly repair satellites in case of failures. Moreover, performance and capability are often more important than cost for military systems. On-orbit upgrades could be used to maintain a high performance and avoid technology obsolescence. Finally, military users are very interested in the capability to refuel satellites in orbit. Refueling can enable new missions and in particular would be of great value to manoeuvre satellites over the location of the conflicts. Therefore the value of on-orbit servicing for military applications could be easily demonstrated.

In addition, national security is a strong political argument that can potentially generate large support. Cost and economic viability are often not the primary decision criteria for military programs. Therefore it could be easier to get support for an expensive and uncertain concept such as on-orbit servicing if it is presented as a military program. Similarly to the highway system, the development of a large on-orbit servicing infrastructure could be defended as a defense program.

However, there are issues with choosing to develop on-orbit servicing as a military infrastructure. Technology transfer to the private sector may be difficult if it is not integrated initially in the program plan. Security issues may arise in particular with respect to transferring the docking interface technology for civil uses. Moreover, the number of military satellites may not be large enough to allow a cost effective servicing infrastructure. However, this could be turned into a strong argument to justify extending the use of the infrastructure to scientific, civil and commercial applications. A more cost-effective infrastructure can be achieved with the increase in demand from non-military users.

On-orbit servicing for a sustainable space industry A non defense policy argument could be constructed around the necessity to ensure a sustainable space industry:

On-orbit servicing has been identified as an effective way to develop a sustainable space industry, through a more cost effective use of space. Therefore, all government satellites should be designed for serviceability and an on-orbit ser-

vicining infrastructure should be developed initially to repair, refuel and upgrade government satellites and then extended to include the service of future non-government serviceable satellites.

This strategy has two promising characteristics. First, this policy has the potential to gain political support. Space systems are recognized as important assets that provide critical services for military, civil and commercial applications. Ensuring a healthy and sustainable space industry is considered as a legitimate and important goal for the US government. On-orbit servicing could offer a new way to consider operations in space and provide more cost effective and flexible space systems. Therefore, on-orbit servicing could be adopted as a way to boost the space market and ensure a sustainable future for the space industry. Moreover, in this strategy, all US governmental satellites would be designed to be serviceable, creating a large initial group of target satellites. The on-orbit servicing infrastructure will be more cost effective with a larger demand. More importantly, the policy will be more effective in stimulating other users to design for serviceability if a larger share of the satellite fleet is already designed to be serviceable. Figure 7-1 illustrates the level of spending of the US government compared to all other worldwide spending. The US spending accounts for a large part of the total amount spent in the world on space systems. Therefore, designing government satellites for serviceability will show a serious commitment to the concept of satellite maintenance and will drive other users to endorse on-orbit servicing.

However, we consider that the two characteristics described in the previous paragraph are not sufficient to make this strategy successful. There is political support for space but it remains limited. If space is considered as an important industry, it must be recognized that space is not a national priority as it was during the Cold War period and budgets for space are not likely to be increased. Space operations are not associated with the economic spill overs and the large contribution to the economic growth of the country that characterized the highway transportation system. In the case of the national highway system, all stakeholders supported the project because they were convinced that the program would generate huge economic and social spill overs and contribute significantly to the economic growth of the country. Space does not benefit from that kind of support. Therefore, the decision to design all governmental satellites for serviceability may appear as too ambitious for the level of political support that characterizes the space industry.

Moreover, justifying the development of on-orbit servicing as a way to ensure a sustainable

US Government spending on space compared to all other worldwide spending (including US commercial)

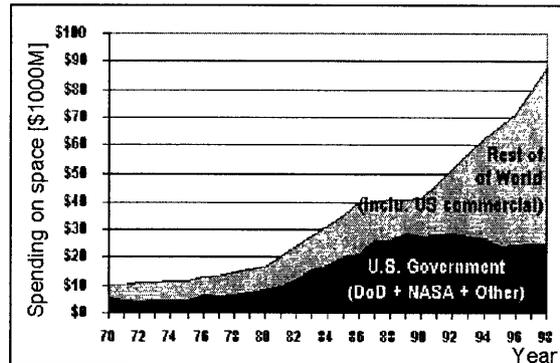


Figure 7-1: U.S. Government spending on space compared to all other worldwide spending/revenues (including U.S. commercial revenues) [14]

space industry may be difficult to defend. On-orbit servicing is not likely to be considered the primary necessity to stimulate the space industry. Most people would identify cheap access to space as the most critical barrier to the expansion of space operations. Therefore, if on-orbit servicing is developed, it may need to be secondary to investments on launch technologies. It is not likely that such an ambitious policy would be feasible as a secondary objective within current tight budgets.

Conclusion After analyzing the potential success of two policy strategies, we believe that if a government funded on-orbit servicing infrastructure is developed, it would likely be as a defense program.

7.4.4 International collaboration

Many space nations are investigating the concept of on-orbit servicing and are conducting research programs both on the study of the value of on-orbit servicing and on technical challenges. A great opportunity could arise if a collaboration could be established between space nations to promote the concept of on-orbit servicing.

An international collaboration could increase the initial demand for on-orbit servicing and allow a more cost effective operation of the servicing infrastructure. Moreover, the different programs could be coordinated and the costs of developing critical technologies and demonstrating safe on-orbit servicing operations could be spread over the different space

agencies. The cost born by each space agency could be lowered, therefore requiring a lower political support to maintain the program. In addition, by adopting a more integrated approach, some harmonization and standardization issues could be prevented. If space agencies work independently on critical technologies for on-orbit servicing, different standards and technologies will likely emerge. Negotiations will then be required to agree on common standards, for the docking interface and the method to access the satellite, in order to enable a competitive, international market for on-orbit servicing. Finally, a large-scale on-orbit servicing infrastructure with the installation of space depots in orbit may require international space nations to collaborate to have an integrated architecture and lower the cost of the deployment and operation of such a large infrastructure.

However, the potential drawbacks associated with partnerships and collaboration must be acknowledged. Issues in technology transfers across nations and intellectual property issues may appear. There is a cost associated with the negotiation process, the potential tensions between partners or partners who fail to fulfill their engagements. The experience gained with the International Space Station can be helpful to limit the burden of collaboration.

The issue of space debris could be a way to bring space nations to discuss the concept of on-orbit servicing and initiate a collaboration. The growing number of non operational objects in space is commonly considered as a serious threat to sustainable operations in space. Many discussions and debates between space nations have been organized around this issue and policies are likely to be announced in the near future. All nations agree on the necessity to regulate the creation of non-operational debris in space. On-orbit servicing can contribute to reducing the number of non operational objects in orbit by reducing the number of launched satellites, by repairing failed satellites, by replenishing satellites at end of life and by saving missions that are not delivered to their operational orbit. Therefore, the issue of space debris could be an enabler to initiate a discussion between international space agencies on the future of on-orbit servicing. On-orbit servicing could even be chosen for implementation as a policy option to mitigate the issue of pollution in space.

7.5 Policy issues in the operation of on-orbit servicing

Other issues are discussed related to the deployment and operation of an on-orbit servicing infrastructure. Some level of standardization and collaboration, potentially at an

international level, is required for the design of the docking interface and the satellite design. The security issues associated with the presence of a standard docking system on-board is also a key concern. Finally, potential liability issues may be raised by servicing providers and users.

Standardization and collaboration Different studies have shown that the use of a servicer for a single servicing operation is not cost effective. Therefore, a servicer must be able to dock with and conduct servicing operations on different target. Some level of standardization is necessary to ensure the compatibility between different targets. The degree of standardization depends on the organization of the market for servicing. It can be imagined that manufacturers could develop their own maintenance servicers and include maintenance as a service for their customers. In this case, the level of collaboration and standardization is limited. However, it is considered more likely that the docking interfaces and to some extent the satellite design will be standardized to ensure a more competitive servicing market and allow more than one provider to dock and service a target. Space manufacturers and government authorities will need to collaborate to agree on standard methods to dock with the satellite, access the satellite subsystems and install replacement units. The choice of the standard may create controversies if different technologies have been invented and patented. International collaboration may also be desirable to allow an international and more competitive market for satellite servicing.

Security The use of a standardized docking interface creates a potential security concern for space operators. Any robotic vehicle could dock with the satellite as long as the docking interface is compatible. The main concerns are for military satellites that could be attacked by enemy vehicles. Military forces are more and more relying on space communications and reconnaissance and military space assets could be a strategic target.

Liability issues Some liability issues associated with the manoeuvres of the servicers between targets and space depots could need to be addressed for a large on-orbit servicing infrastructure.

7.6 Conclusion

Technical challenges are not the only barriers to the development of an on-orbit servicing infrastructure. Major cultural and organizational changes will be required to move from current traditional space systems to serviceable satellites. Such radical changes represent serious challenges to the implementation of on-orbit servicing. Moreover, the feasibility and the value of on-orbit servicing must be proven to convince a risk averse space community. The need for satellites to be designed for serviceability creates a “chicken and egg” problem that is a main hurdle to the development of a private maintenance infrastructure. Private investors have recently shown an interest in the concept of space tugging but it is likely that more innovative operations such as on-orbit repair or upgrade will require some government intervention to overcome an uncertain demand and a risky endeavor. Different policy alternatives, such as tax incentives or public investments in research and development, can be implemented to promote on-orbit servicing. We believe that the most promising strategy would be to develop a government funded on-orbit servicing capability as a defense program. International cooperation could be useful in developing a large on-orbit servicing infrastructure and the policy debate around the space debris issue could be used in the near term as a way to initiate discussions between space nations about the future of on-orbit servicing.

Chapter 8

Conclusion

The main objective of the present study was to investigate the value and attractiveness of on-orbit servicing for satellite upgrades. The valuation has been conducted from the perspective of a potential customer and the value of on-orbit servicing has been defined as the user's willingness to pay. An emphasis has been put on the flexibility offered by on-orbit servicing and the value of the option to physically alter the satellite after it has been deployed. Two case studies have been investigated. The case of the power upgrade of a GEO communication satellite facing an uncertain demand has been chosen as an example of a commercial mission. The upgrade of the payload instruments and the bus subsystems on a scientific observatory has been modelled based on the real case of the Hubble Space Telescope. Finally, the policy aspects associated with on-orbit servicing have been explored to identify major barriers and potential solutions to the emergence of a maintenance infrastructure for space systems.

8.1 Summary

Valuation framework On-orbit servicing offers a way to bring flexibility into space systems, by allowing to physically modify a satellite after it has been deployed. The value of the flexibility must be taken into account when evaluating on-orbit servicing. In Chapter 3, the concept of flexibility and the value of managerial flexibility were defined. It has been shown that traditional valuation techniques such as the Net Present Value method fail to take into account the value of flexibility. Real Options Analysis and Decision Tree Analysis have been presented as dynamic valuation techniques that better capture managerial

flexibility. The framework adopted in the present study has then been described.

Upgrade of a commercial mission facing uncertain revenues The framework has first been applied to the valuation of commercial missions facing market uncertainty. The upgrade of a commercial mission facing uncertain revenues has been investigated in Section 4.4 as a first simple application of the model for the valuation of on-orbit servicing for satellite upgrades. The results demonstrate the importance of dynamic valuation techniques in capturing the real value of on-orbit servicing. The value of the flexibility accounts for a large part of the total value of the mission. The responsiveness of on-orbit servicing appears as a key parameter in the choice of satellite servicing over satellite replacement. Maps of the optimal architecture to implement depending on the satellite environment have been derived to help space users decide whether to upgrade or not the satellite and whether to use on-orbit servicing or satellite replacement. The impact of market conditions and the servicing infrastructure characteristics on the attractiveness of on-orbit servicing have been investigated. Servicing risk appears as a key driver in deciding which method to use to implement the upgrade.

Power upgrade on a commercial GEO communication satellite facing an uncertain demand Chapter 4 investigates the value of using on-orbit servicing to upgrade the solar panels on-board a commercial GEO communication satellite to overcome solar cell degradation. By regularly servicing the satellite to restore BOL power, the satellite capacity could be increased. Few conditions have been found for which on-orbit servicing is attractive. The expected demand for a servicing infrastructure is low in this example, especially for a non zero servicing cost and risk. This result is believed to be mainly due to the characteristics of the example considered. The impact of the upgrade on capacity is limited since the power is only restored to and not increased beyond the BOL power level. Moreover, solar cell degradation is a predictable phenomenon that can potentially be overcome by modifications in the initial design of the satellite. Design modifications, such as using highly resistant solar cells or designing for a higher capacity at beginning of life, often appear as efficient and less risky alternatives to on-orbit servicing. They are often favored over on-orbit servicing as the cost and risk of servicing is slightly increased. No demand for on-orbit servicing is seen once the risk of a catastrophic failure during a servicing operation

is over 5%. The attractiveness of on-orbit servicing as a potential alternative to designing for higher BOL power is then investigated. Finally, it is found that the relation between uncertainty and flexibility value seems to depend on the degree to which the system can adapt to changes. A limited flexibility may not have value if the uncertainty faced by the space operator is too large.

Technology upgrade on a scientific observatory The value of technology upgrades on a scientific mission has been modelled, based on the case of the Hubble Space Telescope, a unique example of an unmanned scientific platform initially designed to be regularly serviced by the Space Shuttle. The impact of the repair of the spacecraft, the installation of new instruments and the upgrade of bus subsystems are included. A Monte Carlo simulation is used to model uncertainty in the arrival of new technologies, random spacecraft failures and catastrophic failures of a servicing operation. The installation of new more capable instruments and of new technologies to ensure compatibility of the bus with the upgraded payload can provide a huge increase in the scientific utility of the mission. A huge increase in mission utility can be achieved at a lower cost than if the satellite had been replaced. The value of upgrading increases as the rate of innovation accelerates. If a servicing mission is risky, a trade off appears between upgrading more often to achieve a higher utility and the increased risk of losing the satellite as the number of servicing missions increases. The decision model used by decision makers defines the upgrade strategy, which can vary between upgrading as soon as a new technology appears or waiting until the impact of the innovation is large enough to be considered worth the cost of the servicing mission. The main differences between manned servicing operations, similar to the maintenance operations conducted on the Hubble Space Telescope, and unmanned robotic missions are then examined. In particular, the impact of the risk and cost of servicing on the mission utility is investigated.

Conclusions on the attractiveness of on-orbit servicing for satellite upgrades By comparing the results obtained in the two case studies presented, we can derive two conditions that seem to determine the attractiveness of on-orbit servicing for satellite upgrades. On-orbit servicing appears promising first when the increase in mission utility achieved by the upgrade is large and second if there are no other alternatives that can provide a similar increase in mission utility for a lower cost of lower risk.

Policy barriers and enablers to on-orbit servicing On-orbit servicing represents a major shift in the way space systems are designed and operated. Major cultural and organizational modifications will be required within the space community before on-orbit servicing can be adopted as the new paradigm in space systems. The space industry is traditionally resistant to changes and largely risk averse, which reinforces the scepticism for on-orbit servicing. Moreover, the need for satellites to be initially designed for serviceability creates a vicious circle and a failure of market forces. No on-orbit servicing infrastructure will be developed without the existence of a demand. And no demand for on-orbit servicing will exist before a servicing operation is offered, because no satellite will be designed for serviceability until a servicer is available. Private investors may be interested in some maintenance applications, such as space tugging, that can service existing satellites and that aim at less risky operations on failed satellites or satellites at end of life. For a more innovative and large scale on-orbit servicing infrastructure, an external government intervention is believed to be necessary. The policy we believe is most likely to succeed in promoting on-orbit servicing is to commit to serviceability for military satellites and to develop a government funded on-orbit servicing infrastructure as a defense program.

8.2 Recommendations for future work

Satellite upgrade is a very challenging issue and this work is only a first step in investigating the potential attractiveness of on-orbit servicing for satellite upgrades. Many questions are still to be answered, in particular with respect to designing for modularity, determining which modules are the most promising candidates for upgrade and investigating interactions and compatibility issues between modules.

Modular design The scope of the upgrades that can be performed depends largely on the initial design of the satellite. A modular design will need to be adopted to enable satellite upgrade. What criteria should be chosen to drive the definition of the module boundaries? The failure rate of components, the pace at which the technologies embedded in the system evolve, the impact of the system on the utility of the mission and the complexity of required interfaces with other systems are likely to be considered when deciding on which systems to group in the same module. Defining the parameters that drive the definition of module boundaries will help understand the complexity and feasibility of an upgrade.

System simulation Satellite upgrade is much more complex to model than satellite repair or refueling because changing a module affects the system and the satellite performance. The consequences of an upgrade on the utility of the mission, the effects on other subsystems and the constraints imposed by existing on-board systems are both critical and delicate to model and estimate. A detailed system simulation could be very useful in understanding the implications of distinct module upgrades on the value of the mission and subsystem compatibility. The simulation could be used to track the effects of a module modification through the system and get a better understanding of the feasibility of an upgrade and the consequences of an upgrade on the overall mission.

Most promising candidates for upgrade Determining what are the most promising modules for upgrade would provide great insights on how to design the initial satellite for upgradeability. Good candidates would likely be the modules that have a large impact on the utility of the mission, for which technology is rapidly evolving and that can be to some extent isolated from other subsystems so that interfaces are easy to manage.

Provider perspective The on-orbit servicing provider's perspective should be investigated to conclude on the economic viability of an on-orbit servicing infrastructure for satellite upgrade. The conclusions derived from the study of the customer's perspective can be used as the demand side of the market. Depending on cost and policy considerations, the supplier side can be analyzed before concluding on the conditions for the development of a profitable maintenance infrastructure for satellites.

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