Calculations of Flexibility in Space Systems

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Abstract

One of the important aspects of Engineering Systems design is the measurement of flexibility. In this paper, different measures for flexibility are applied to an orbital transportation network (Hastings and Nilchiani, 2002) [1]. This network provides an on-orbit servicing capability. While the case studies discussed here are focused on space systems, these measures of flexibility can also be expanded to many other engineering systems.

The flexibility for an orbital transportation network can be calculated using the combination of three types of flexibilities, which play out in different time frames: Mix flexibility (long-term), volume flexibility (mid-term) and emergency service flexibility (short term), which can all be categorized as provider-side flexibilities (Nilchiani and Hastings, 2003) [2]. Mix flexibility is defined as the strategic ability to offer a variety of services with the given system architecture. Volume flexibility is the ability to respond to drastic changes in demand. Emergency service flexibility is the tactical ability of the system to provide emergency (non-scheduled) services to satellites in duress. The overall provider-side flexibility metric is then obtained by taking the weighted average of the above flexibilities. The provider, based on the priorities specified in the orbital transportation network mission objectives, determines the weight coefficients.

The case of the Hubble Space Telescope, first unmanned satellite designed to be regularly serviced using the Space Shuttle, offers a unique real example to study the value of the flexibility from the perspective of the customer of a scientific space mission. Three sources of flexibility are investigated: the capability of repairing the observatory, of upgrading the payload instruments and of upgrading the bus subsystems against technology obsolescence. A model of a scientific space platform is developed from the

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Hubble example and the value of the flexibility is estimated using a Monte Carlo simulation. The impact of different design choices and degrees of flexibility on the utility and cost of the mission are presented.

These two sets of approaches to calculating flexibility for space systems highlight the different ways flexibility can be valued, be it in terms of flexibility metrics or real option values. The choice of methodology depends on the context and the engineering system in question, as well as what kind of outputs are expected.

Introduction

There is increasing emphasis on the value of flexibility in the design of engineering systems. According to Saleh et al. (2001) [3], Flexibility can be defined as "a form of meta-control aimed at increasing control capacity by means of an increase in variety, speed, and amount of responses as a reaction to uncertain future environmental developments"

Flexibility has been categorized along different dimensions. Looking at manufacturing systems, Merchant (1983) [4] makes a distinction between different flexibilities on a temporal basis. In his treatment of flexibility, he distinguishes between instantaneous flexibility (the ability to immediately select the most suitable work center for carrying out the operation required by the work cycle of a certain part), very short-term flexibility (the ability to modify the sequence and mix of the parts produced), short-term flexibility (the ability to modify certain design specifications of the parts of the products), short- to medium-term flexibility (the ability of the system to work at the maximal levels of productivity when production volumes are varied), medium-term flexibility (the possibility to add or eliminate parts from the mix of parts being produced), medium- to long-term flexibility (the possibility to modify the manufacturing capacity by adding or eliminating work centers), and finally long-term flexibility (the possibility to adapt the system to new types of products or mix of components).

Benjaafar and Ramakrishnan (1996) [5] propose a “flexibility hierarchy” that divides system flexibility between product- or service-related flexibility and process flexibility.

Product-related flexibility includes operation flexibility, sequencing flexibility, and processing flexibility, while process-related flexibility is defined along processor flexibility, mix flexibility, volume flexibility, layout or configuration flexibility, and component flexibility. Zhang et al. (2003) [6] define different types of *manufacturing flexibility* for firms. They define *volume flexibility* as the ability of the organization to operate at various batch sizes and/or at different production output levels economically and effectively. It demonstrates the competitive potential of the firm to increase production volume to meet rising demand and to keep inventory low as demand falls. *Mix flexibility* is defined as the ability of the organization to produce different combinations of products economically and effectively, given certain capacity. It enables a firm to enhance customer satisfaction by providing the kinds of products that customer's request in a timely manner. Mix flexibility must be evaluated within the current production system configuration without considering major facility modifications. This implies that the production system can respond to changes in demand without impacting volume and capacity, which are parts of volume flexibility.

With regard to space systems, Saleh et al. (2002) [7,8] have analyzed customer-side flexibility as one of the inherent values of a space system. They provide a framework to account for the value of the flexibility provided by on-orbit servicing to space systems. The framework is applied to studying the value of servicing for two types of space missions: commercial missions with uncertain revenues and military missions faced with uncertainty in the location of contingencies. In the first case, they argue that the traditional valuation has been underestimating mission value by not taking into account the option to abandon. In the second case the value of refueling for making spacecraft maneuverable showed that for a radar constellation in low Earth orbit, servicing had little value due to a conflict between propulsion mass and maneuver time; whereas for a geostationary fleet of communication satellites, servicing is shown to have value based on the potential improvements in capacity usage.

Saleh et al. (2003) [9,10] also propose a new customer-centric perspective on on-orbit servicing, where the value of on-orbit servicing is studied independently from its cost. They develop a framework that captures the value of flexibility provided by on-orbit servicing to space systems. Several options are made available to space missions through on-orbit servicing, such as the option to service for life extension or to upgrade, that need not be set before launch; they can be exercised after the spacecraft has been deployed, depending on how events unfold (market changes, new military contingencies, etc.). They argue that only by accounting for this flexibility can the true value of on-orbit servicing be evaluated.

In this paper, different measures for flexibility, applied to different space systems such as an orbital transportation network (Hastings and Nilchiani, 2002) [1] for providing an on-orbit servicing capability are studied and their impact on the design of space systems architecture is explored. While the case studies are focused on space systems, these measures of flexibility can also be expanded to many other engineering systems.

Provider-Side Flexibility for the Orbital Transportation Network

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

Flexibility is necessitated by uncertainty. De Toni et al. (1998) [11] argue that flexibility is needed in case of (1) the variability of the demand (random or seasonal); (2) shorter life cycles of the products and technologies; (3) wider range of products; (4) increased customization; (5) shorter delivery times.

In this paper, the focus on flexibility in the case of the Orbital Transportation Network is on *provider-side flexibility* for space systems. It adapts to and expands on manufacturing flexibility concepts to define provider-side flexibility for space systems. While customer-side flexibility represents part of the value assessment of a space system, it gives little insight into which system architectures provide the most flexibility for the service provider. Defining a flexibility metric, taking into account the different types of uncertainties any service may be facing, is an important step towards robust space architecture design. The flexibilities explored in this paper thus complement the customer-side flexibilities proposed by Saleh et al. (2003) through consideration of provider perspectives.

Service flexibility for an orbital transportation network can then be defined as the combination of three types of flexibilities, which play out in different time frames: *Mix flexibility* (long-term), *Volume flexibility* (mid-term), and *emergency service* flexibility (short term).

Mix flexibility is the strategic ability to offer a variety of services with the given system architecture. In the context of the orbital transportation network the types of services that can be provided by the system include: on-orbit refueling, servicing, upgrading, and tugging of satellites, as well as less crucial services such as housing scientific instrumentation within the existing infrastructure. In this research the mix flexibility is defined as the ratio of profit resulting from adding more service types, taking into account additional cost incurred by the necessary changes in architecture, to the profit with a single service only. Mix flexibilities larger than 1.0 indicate a system that increases in value by offering multiple service types. For this purpose, mix flexibility is defined by Equation 1,

$$f_m = \frac{S_m - E_m}{S - E} \quad , \qquad (1)$$

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

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

$$f_v = \frac{\int_0^E e^{-rt_m} (S - E) p(S) dS}{I_{Risk-free}}, \qquad (2)$$

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

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

$$f_E = \frac{Cap_{\max}}{Cap_{current}} \qquad (3)$$

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

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

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

Combined service flexibility can be defined by a weighted sum of the above flexibilities. The weights would reflect the value of each of the types of flexibility for the design team. Nilchiani and Hastings (2003) [2] have explored the different combinations of flexibilities based on the applications to commercial and military satellite refueling and servicing and their impact on space systems architecture design. In a previous research on orbital transportation network (Hastings and Nilchiani, 2002) [1], optimal architectures were explored in terms of a value metric, which signified the economic feasibility of refueling missions, and a performance metric, which represented the reliability and availability of refueling services. As Figures 1-3 show, adding the flexibility dimension changes the Pareto optimal architectures in terms of the Depot-Orbital Maneuvering Vehicle (OMV) configuration. In this particular instance, a (2 OMVs, 3 Depots) optimal architecture is replaced by a (4 OMVs, 5 Depots) architecture. This shows how taking into account flexibility can affect the choice of optimal architecture in a way that the system becomes somewhat more expensive, but can handle volume-level, service-mix and emergency-service uncertainties and fluctuations inherent in on-orbit servicing operations.

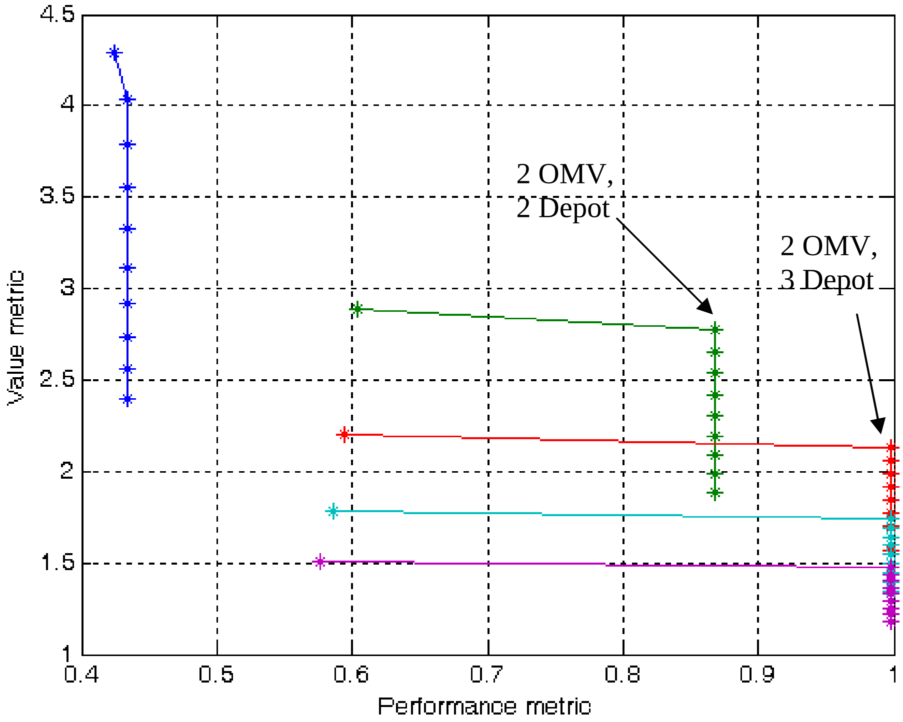

Figure 1. Optimal architectures based on value and performance metrics. (Based on a refueling price of $8 million per satellite and a client set of 110 satellites).

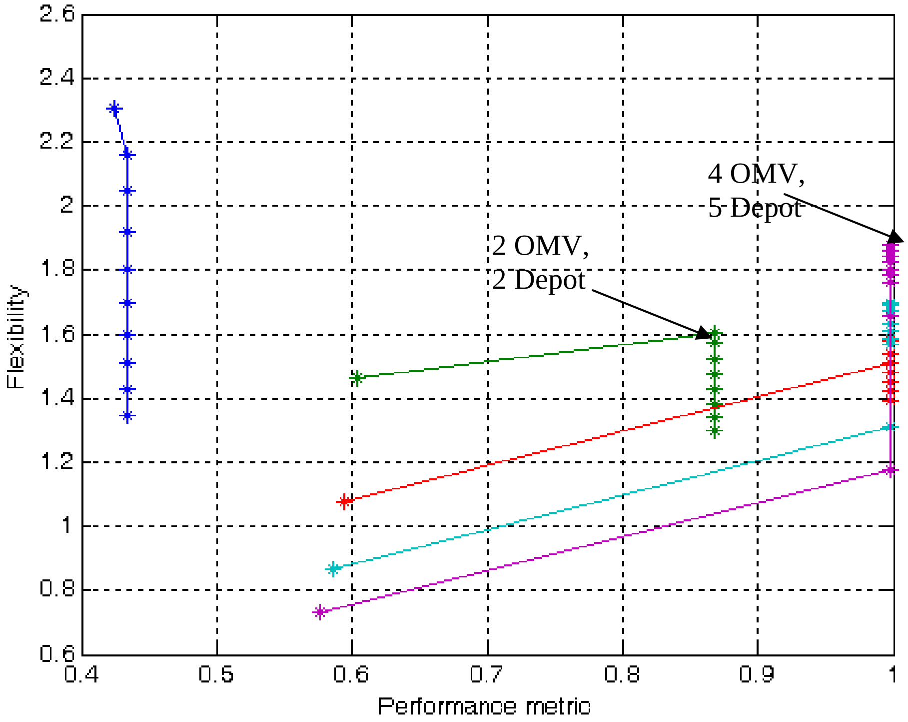

Figure 2. Optimal architectures based on performance metrics and flexibility. (Based on a refueling price of $8 million per satellite and a client set of 110 satellites, we assumed w_v=0.2, w_E=0.7, w_M=0.1).

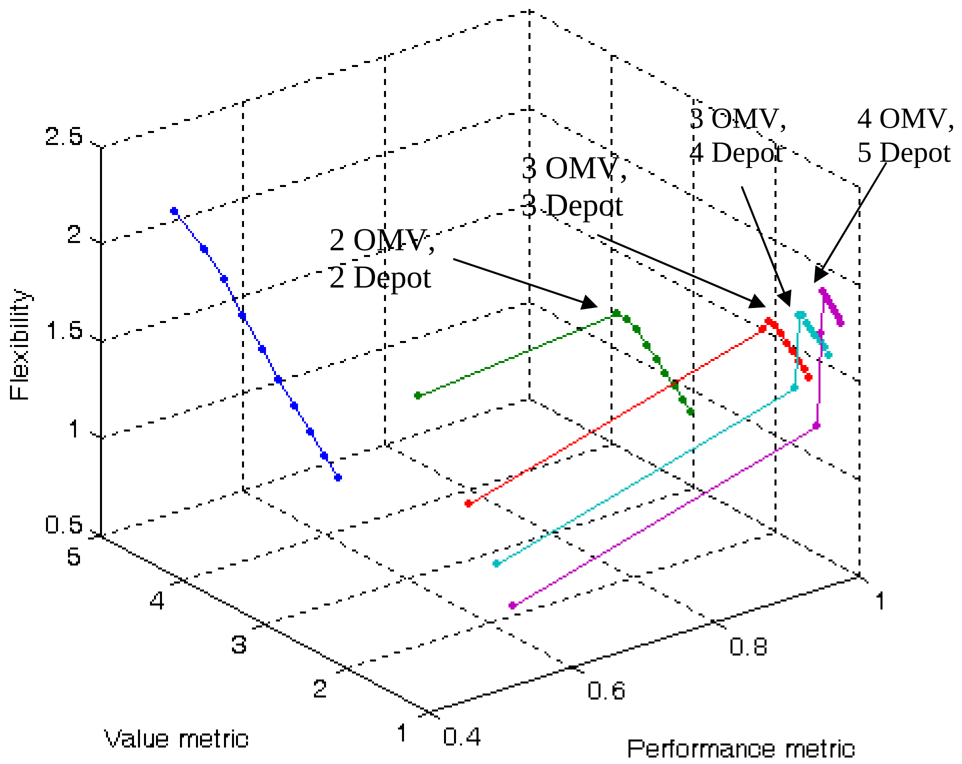

Figure 3. Optimal architectures based on value metric, performance metric and flexibility metric. (Based on a refueling price of $8 million per satellite and a client set of 110 satellites, we assumed w_v=0.2, w_E=0.7, w_M=0.1).

Note the interesting trade between value and flexibility in Fig. 3. The provider of the OTN service would want to choose the highest value architecture associated with the highest performance. This is the 2 OMV, 2 depot architecture associated with providing services to the GEO ring. However, this architecture is less flexible than the 4 OMVs, 5 depot architecture for essentially identical performance. Thus the provider must take the risk of choosing greater return (highest value) now against the possibility that the market may change or the customer has some emergency needs (greater flexibility) that he cannot meet. This in this case, flexibility and value seem to trade against each other.

Customer-side Flexibility for the Hubble Telescope

Space systems are characterized by a large initial investment and 15-20 year design lifetime to increase the return on investment. No maintenance capability is available for most space systems. The traditional approach is to build-in reliability in the satellite and to replace the system in case of obsolescence or failure. This lack of flexibility may translate to risk for the system operator: risk of system failure, risk of technology obsolescence, risk of commercial obsolescence or risk of change in the users' requirements. Flexibility, defined by Saleh (2001) [3] as the ability of a system to adapt and respond to changes in its initial objectives, requirements and environment occurring after the system is in operation in a timely and cost-effective manner, can partially protect the operator against risk and transform uncertainty into new opportunities.

On-orbit servicing could change the current space system design paradigm by providing flexibility to space systems' customers and operators. The Hubble Space Telescope, launched in 1990, is the only space platform ever designed to be regularly serviced by the Space Shuttle and is therefore a unique opportunity to analyze the value of the flexibility provided by on-orbit servicing from the perspective of the space system customer.

Different types of customer-side flexibility will first be presented. Historical data from the Hubble Space Telescope will then be described as an example of the potential benefits gained from system flexibility. Finally, a model of a serviceable scientific space observatory, developed from the Hubble telescope example, will be presented in an attempt to quantify the value of the flexibility offered by repairing and upgrading a scientific space system.

Types of customer-side flexibility

When adopting the point of view of a space operator, the sources of flexibility may be classified by looking at their effect on the space mission. Saleh (2001) [3] proposes three different categories classified 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 aim at improving the operational system in meeting them.
- *A mission change* characterizes an operation that aims at modifying the mission the satellite was initially performing.

The Hubble Space Telescope example

The Hubble Space Telescope (HST) was designed in the 1970s and deployed on April 25th 1990 by the Shuttle Discovery. A total of four servicing missions have been performed to make the Hubble Space Telescope a state of the art observatory along the 13 years it has been operated. The rationale for designing the Hubble Space Telescope for serviceability was to reproduce in space the equivalent of an observatory on Earth. 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 and flexible 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.

- Mission salvage: The ability to service the Hubble Space Telescope made it possible to save the mission. A 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.
- 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 repairing problems that were not expected in the initial design of the vehicle. For example, it was not expected that the non-rigid structure of the solar panels would cause them to oscillate creating disturbances in the observations. 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.
- 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 performances 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.

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.

Evaluating customer-side flexibility

When studying the value of the flexibility, both the potential benefits and costs must be taken into account. The costs encompass the cost of designing for flexibility and the cost of using the flexibility when modifying and adapting the system as desired. In particular, in the case of on-orbit servicing of space systems, there is a cost associated to designing the satellite for serviceability, and a cost and a risk associated with the on-orbit servicing operation itself.

The valuation framework used to analyze the value of on-orbit servicing is highly dependent on the mission studied and on the interests of the operator and customer. The use of real options as proposed by Saleh and al. (2003) [8] has been successfully applied to commercial missions such as the refueling of GEO communication satellites and the upgrade of the solar panels on commercial GEO communication satellites (Joppin, 2003) [12.13]. For a scientific mission such as the Hubble Space Telescope, the utility is difficult to express in monetary units and the goals pursued are often very different from commercial operators. Financial methods such as real options are difficult to apply. We chose to use a Monte Carlo simulation to evaluate the flexibility value for a scientific observation space platform.

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, chosen as the instrument discovery efficiency, is defined to capture the scientific return of the mission. This measure, often used to describe and compare the capacity of observation cameras by astronomers, 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. 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. A more detailed description of the model can be found in Joppin (2003). First some results will be presented that indicate that designing for serviceability can significantly increase the mission utility. We will then discuss how such a model can be used by designers and operators in deciding on system design choices.

Mission utility for a flexible architecture

Figure 4 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 non flexible satellite. We will refer to a non-flexible architecture (no upgrade and no repair are possible) as the 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. 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.

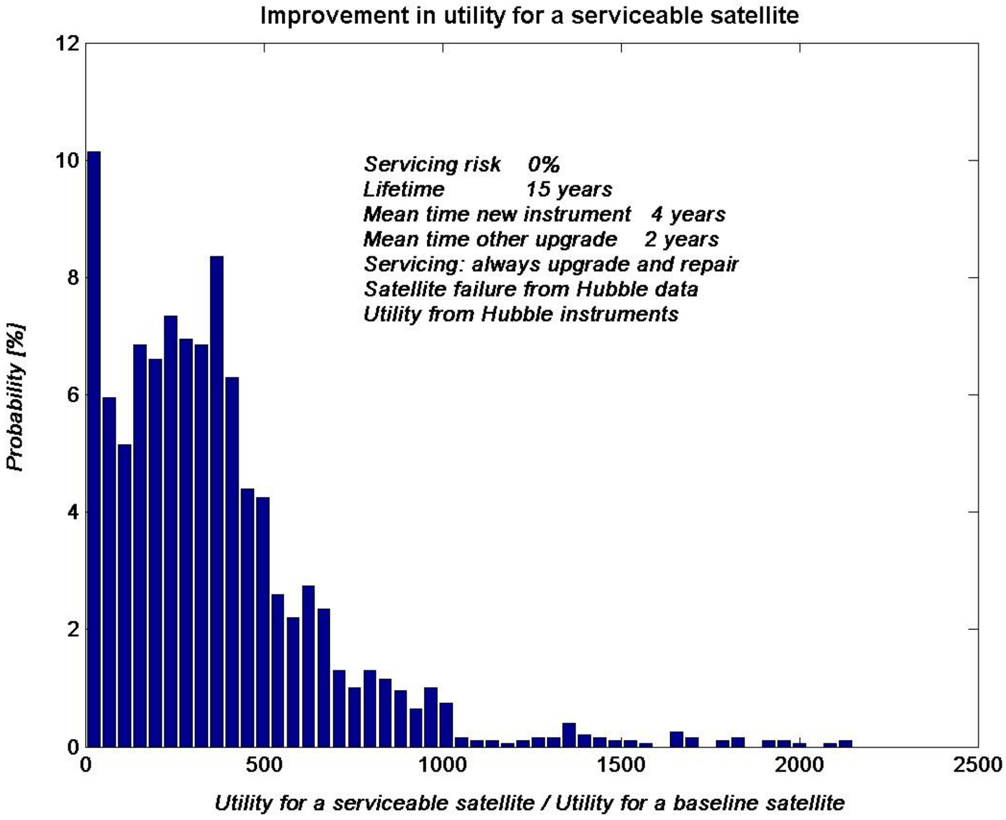

Figure 4. Probability distribution of the improvement in utility achieved with a serviceable satellite.

The risk of catastrophic failure of a servicing mission causes a major change of the mission utility distribution as illustrated in Figure 5. 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%.

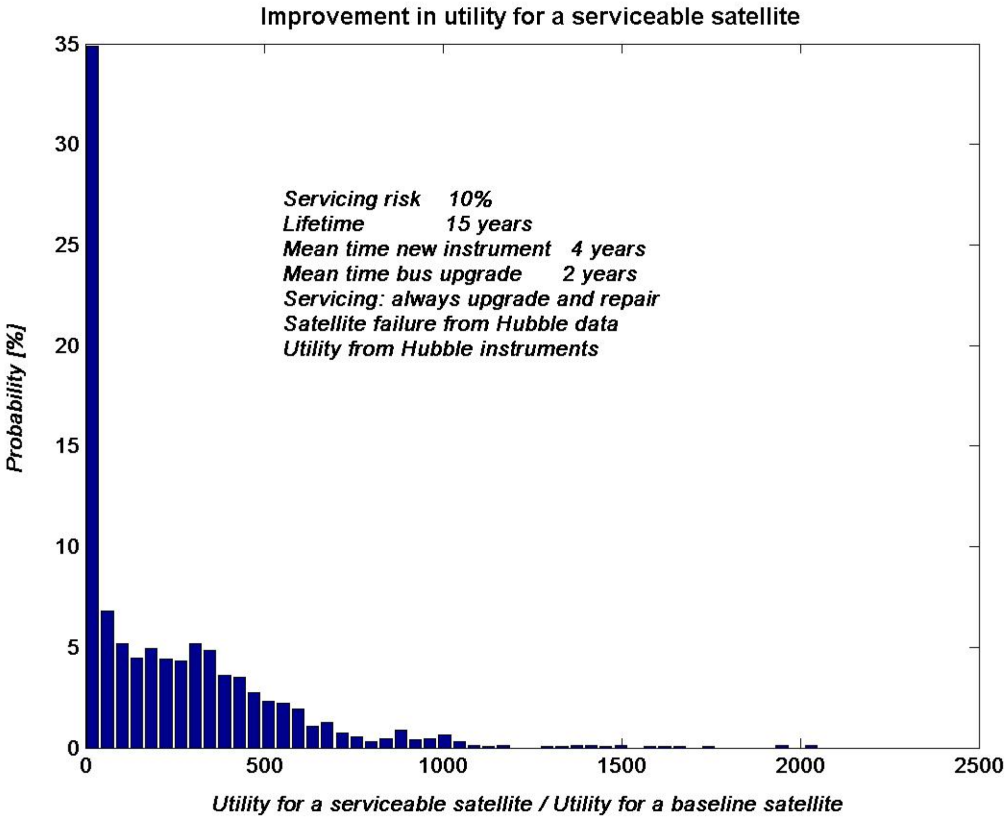

Figure 5. Probability distribution of the improvement in utility achieved with a serviceable satellite assuming a 10% servicing risk

Upgrading and repairing the satellite can significantly increase the utility of the space mission. The characteristics of the servicing infrastructure, in particular the risk of a servicing operation, are critical in determining the flexibility value.

System design choices

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. A trade off exists between regularly repairing the satellite in orbit and designing the satellite for a higher level of reliability. The impact of such design choices relating to the level of redundancy or the serviceability of the satellite can be explored using the model. The effects of different servicing costs and risks on mission utility and lifetime costs are shown in Figure 6. A baseline satellite refers to a non-flexible architecture (no upgrade and no repair are possible). For Figure 6, it is assumed that the flexible satellite can be repaired if deemed necessary and is always upgraded as soon as a new technology appears. The mean utility is normalized to the average utility offered by a baseline redundant satellite.

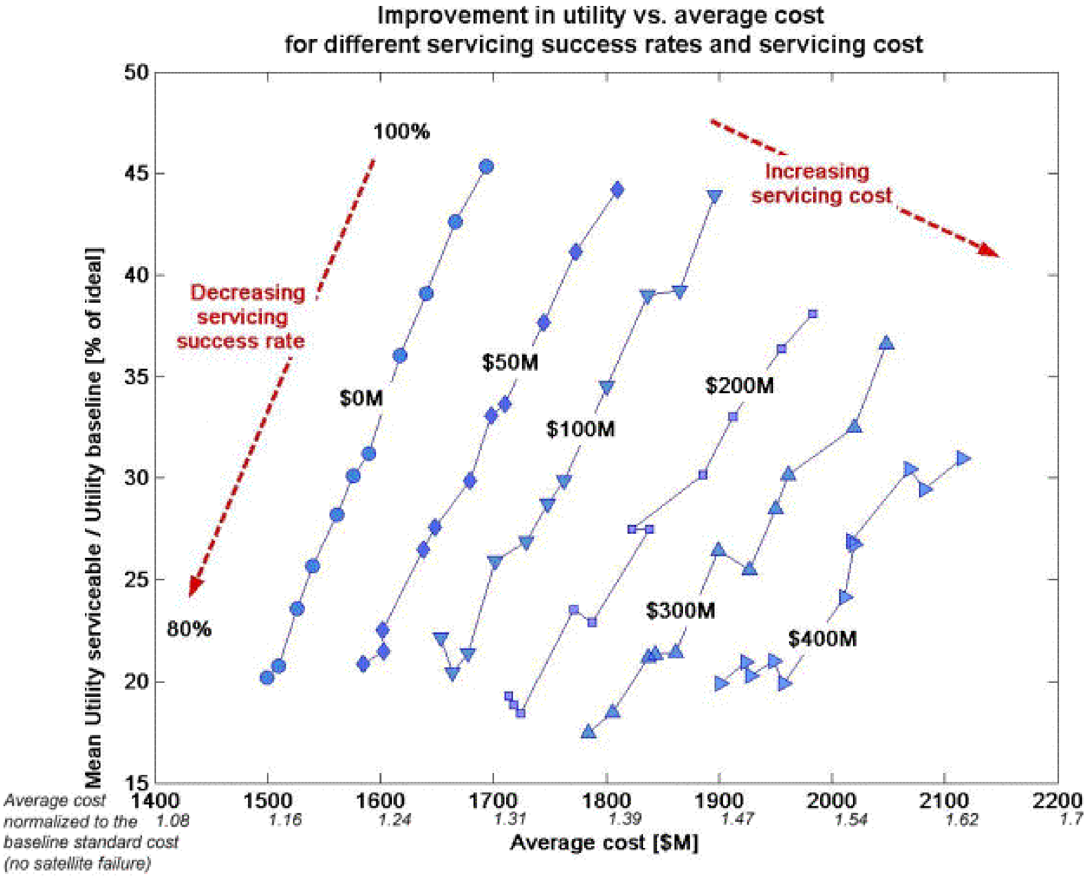

Figure 6. Impact of various servicing costs & servicing success rates on the mission utility and total cost of the architecture.

Figure 6 shows that in the most optimistic case (servicing costs nothing and has no risk), the mean improvement of utility is 45% of the ideal case (the maximum possible) while the average cost is only about 30% greater than the baseline system. Since without the flexibility associated with servicing the customer would have had to replace the system (and thus double the cost), the flexibility discussed here has a substantial cost savings associated with it. Of course, servicing is not cost free and there is some risk. In the case where the servicing costs $400 million (what NASA says it costs) we see that the increase in utility is about 30% for an average cost increase of 62%. Thus we conclude that for the only case for servicing where actual data exists, the flexibility associated with servicing comes at substantially smaller cost than replacing the system. Thus unlike the previous examples of the OTN, where the provider had to choose between value and flexibility, in this case flexibility saves money and thus delivers increased value. The fundamental reason for this is that the change in utility associated with servicing & flexibility is so large (up to three orders of magnitude) that it is hard to achieve similar changes for less cost. This indicates that tradeoff between flexibility, value and performance is complex and most be evaluated carefully to understand the correct set of choices to make to deal with uncertainty.

Conclusion

This paper presented different types of flexibility from the provider and customer-side perspectives for on-orbit servicing and refueling. It provided ways to calculate provider-side flexibilities such as volume flexibility, mix flexibility and emergency flexibility for orbital transportation networks. These provider-side flexibilities could be combined into a single flexibility metric that can be used by providers to determine the architecture with the best combination of value, performance and flexibility, based on provider preferences. On the customer-side, the paper analyzed mission utility for flexible an non-flexible architectures in the on-orbit servicing of the Hubble space telescope and concluded that the feasibility of designing flexibility into space systems for serviceability would be highly dependent on the cost of a servicing mission, and may be more feasible if used in conjunction with refueling and upgrading of units. The analysis in this paper shows how the calculation of flexibility can help decision-making for satellite and space telescope operators as well as on-orbit service providers faced with different types of uncertainty.

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