CRANFIELD UNIVERSITY

TIAGO HENRIQUE MATOS DE CARVALHO

A CONCURRENT ENGINEERING FRAMEWORK TO EXPLORE THE SERVICER-CLIENT RELATIONSHIP IN ON-ORBIT SERVICING

SCHOOL OF AEROSPACE TRANSPORT AND MANUFACTURING
SPACE RESEARCH GROUP

PHD IN ASTRONAUTICS AND SPACE ENGINEERING
Academic Year: 2014 - 2018

Supervisor: Dr. Jennifer Kingston
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This thesis is submitted in fulfilment of the requirements for the degree of PhD in Astronautics and Space Engineering

ABSTRACT

The implementation of On-Orbit Servicing (OOS) in the development and operation of space systems has been pursued to enable inspection, maintenance, repair and assembly of systems in space. Performing such tasks robotically involves the consideration of two sides, a Servicer satellite performing the necessary tasks and a Client satellite receiving it. A critical point for a realistic consideration of OOS demands the concurrent approach of both sides. Despite the current interests towards OOS, there is still a gap in the research into the relationship of Client and Servicer.

This research aims to develop and demonstrate a methodology to technically incorporate On-Orbit Servicing, at a system-level, to the mission design process and operation of current and new satellites

The first objective deals with the systematic arrangement of the current available knowledge. A top-down approach is used to provide a taxonomy of servicing, followed by the functional decomposition of the main tasks. This objective clarifies the main issues observed today in OOS, directly related to the Client-Servicer relationship.

The second objective is to establish the proposed framework. Agent Based Modelling and Simulation is used to implement the main guidelines and concept of operation, and to output different metrics to allow users (Servicers and/or Clients) to evaluate the attractiveness of various OOS scenarios. The mathematical background for the different metrics is defined and discussed. This is complemented by a solution exploration feature for specific types of OOS. A set of cases is presented based on current interests of operators, providing coverage of potential scenarios to use the framework.

The proposed objectives are met, achieving the main research aim. The results help to illustrate the effects of servicing in the systems design and operation. Features of the framework expand the capacity to identify potentially attractive conditions for both sides. Such characteristics are not observed in the current published research and represent a powerful tool to be employed at early stages of design and procurement.

Keywords: On-Orbit Servicing, relationship approach, concurrent framework, Servicer, Client, Agent Based Model and Simulation

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LIST OF ABBREVIATIONS

ABMS	Agent Based Model and Simulation
ADR	Active Debris Removal
AR	Acceptance Review
ATV	Automated Transfer Vehicle
BOL	Beginning of Life
CDR	Critical Design Review
CER	Cost Estimating Relationship
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
COSEMS	Comprehensive Operational Support Evaluation Model for Space
CRR	Commissioning Result Review
DARPA	Defense Advanced Research Projects Agency
DES	Discrete Event Simulation
DTA	Decision Tree Analysis
ECSS	European Cooperation for Space Standardization
ELR	End-of-Life Review
EOL	End of Life
ETS	Engineering Test Satellite
EVA	Extra Vehicular Activity
FRR	Flight Readiness Review
GEO	Geostationary Earth Orbit
GSV	Geostationary Servicing Vehicle
GTO	Geosynchronous Transfer Orbit (Geostationary Transfer Orbit)
HST	Hubble Space Telescope
HTV	H-II Transfer Vehicle
ISRU	In-Situ Resource Utilisation
JEMREMS	Japanese Experiment Module Remote Manipulator System
LE	Lifetime Extension
LEO	Low Earth Orbit
LRR	Launch Readiness Review
MCR	Mission Close-out Review
MDR	Mission Definition Review
MEV	Mission Extension Vehicle

MR	Maintenance and Repair
NPV	Net Present Value
OMV	Orbital Manoeuvring Vehicle
OOS	On-Orbit Servicing
OOM	On-Orbit Manufacturing
ORR	Operational Readiness Review
ORU	Orbital Replacement Unit
PDR	Preliminary Design Review
PRR	Preliminary Requirements Review
QR	Qualification Review
RPO	Rendezvous and Proximity Operations
RRM	Robotic Refuelling Mission
RSGS	Robotic Servicing of Geosynchronous Satellites
SIS	Space Infrastructure Services
SPDM	Special Purpose Dexterous Manipulator
SM	Standard Metric
SMM	Solar Maximum Mission
SRR	System Requirements Review
SSL	Space Systems/Loral
TORU	Teleoperated Control System
TRL	Technology Readiness Level
UDF	User Defined Function
USAF	United States Air Force

NOMENCLATURE

a	Semi-major axis in km
a_{phase}	Semi-major axis for phasing manoeuvre in km
β	Weibull shape parameter
C_0	Cost as new in M$
C_{OpCost}	Cost of operations per year in M$
C_{resid}	Residual cost in M$
ΔV_{phase}	ΔV for phasing manoeuvre in m/s
$fail_{rate}$	Failures per year
$fail_{cap}$	Capacity loss due to failure in % of total capacity
i	Orbital inclination in degrees
$k_{servicer}$	Number of Servicer revolutions before rendezvous
k_{client}	Number of Client revolutions before rendezvous
μ	Gravitational constant in km^3/s^2
m_0	Satellite total mass in kg
m_f	Satellite dry mass in kg
m_p	Satellite propellant mass in kg
$m_{prop\text{-}sell}$	Mass of sellable propellant in kg
n_c	Number of Clients
n_s	Number of Servicers
$prop_{life}$	Propulsion type for operation
$prop_{insertion}$	Propulsion type for orbit insertion
$profit$	Servicer intended profit at EOL in % of total cost
θ	Weibull scale parameter in years
θ_{phase}	Phase angle (Servicer and Client angular separation) in degrees
Ω	Orbital slot (GEO) in degrees
ω_{client}	Client angular velocity in deg/s
Orb	Starting orbit
r	Discount rate
$Serv_{type}$	Desired type of servicing
t_{sim}	Simulation time in years
t_{Life}	Design life in years
t_{start}	Operation start time in years
T_{obs}	Obsolescence time in years
$t_{extended}$	Desired extension time in years
t_{serv}	Expected time to be serviced in years
t_{fail}	Time of failure in years
T_{phase}	Time for phasing manoeuvre seconds
$TTBE$	Time to Break-Even in years

1 Introduction

This chapter presents the overall introduction of this research. The current state of the art and a brief contextualization are presented in the first section. Aim and objectives are presented and linked to the research structure, concluding with the novelties of this research.

1.1 Background and Motivation

On-Orbit Servicing (OOS) is one solution that has been explored throughout the history of space missions, aiming at the inspection, motion, maintenance, repair and assembly of a system in space.

The state of the art for On-Orbit Servicing (OOS) today encompasses three main pillars. The first pillar covers a comprehensive heritage in the areas of space robotics developed through the history of space missions for non-servicing activities. Specific disciplines of autonomous navigation and control, rendezvous and docking, and general space robotics are examples of this heritage.

The development of dedicated servicing systems, subsystems, and technology demonstrators compose the second pillar, with a limited number of missions performed in space. Herein, examples such as the capture of targets, visual navigation, parts manipulation and refuelling are part of the development and demonstration with focus on OOS. This second pillar also encompasses the demonstration of how servicing could be done using dedicated robotic systems interacting with a specific target to be serviced.

Finally, the current increase in the commercial appeal of servicing defines the third pillar of the current servicing state of the art. The current proposition of commercial servicing systems, known as Servicers, has increased the interests of various satellite operators in being a potential Client of different commercial servicing options. Among the interests in commercial servicing is the potential extension of life, improvement of the operation through-life, response to failures and even assembly in space.

Figure 1-1 highlights the current state of the art.

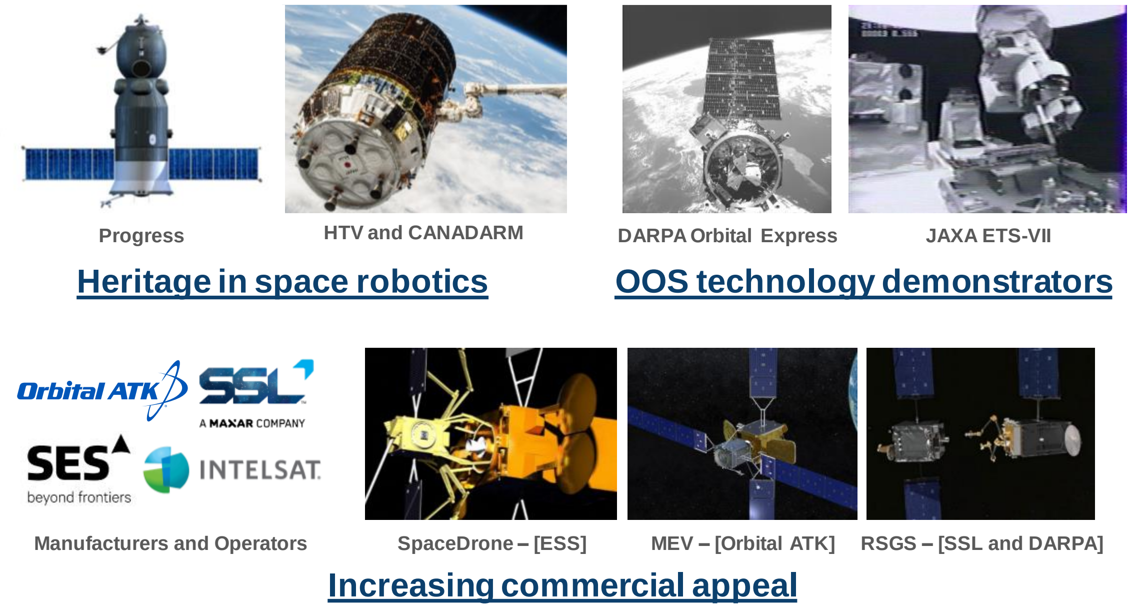

Figure 1-1 – State of the art for On-Orbit Servicing

These three major areas contribute to present OOS as a trending subject today among satellite operators and manufacturers, especially regarding the implementation of servicing solutions.

However, the interaction between such pillars is not enough for the implementation of servicing solutions as part of the development of space systems and operation. The lack of understanding and consideration of the systemic link between the two main actors of servicing, Client and Servicer, is the main problem to be addressed. Each of these actors have their own technical, operational and organizational characteristics defined by their operators.

This background provides the motivation for this research and for the definition of the thesis aim and objectives, presented in the following section.

1.2 Aim and Objectives

Within the context presented for On-Orbit Servicing, the aim of this thesis is:

To develop and test a methodology to technically incorporate On-Orbit Servicing, at system-level, to the mission design process and operation of current and new satellites.

The key objectives and their specific tasks are stated as follows:

1. **To identify the On-Orbit Servicing (OOS) capabilities and the influence of OOS on the lifecycle of a Client spacecraft and operation of a Servicer spacecraft.**
    1.1. To analyse the different OOS concepts proposed and developed to date.
    1.2. To identify the main OOS definitions and applications.
    1.3. To relate OOS applications to the design and operation phases of serviceable satellites.
    1.4. To identify, analyse and discuss the implementation issues related to OOS.
    1.5. To define a taxonomy of the Servicer side.
    1.6. To analyse the functions from each OOS concept.
    1.7. To define a high-level functional decomposition of servicing.
    1.8. To analyse the technological maturity of servicing functions and applications.

2. **To establish and operate the framework capable to incorporate Technology Readiness Levels [1], business models and user needs to simulate the interaction of Servicer and Client.**
    2.1. To identify a modelling methodology capable to simulate the relationship between Servicer and Client.

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[1] The definition of Technology Readiness Level used herein follows the European Cooperation for Space Standardization (ECSS).

2.2. To define metrics of value, other than cost, of a space system throughout the operational lifetime.
2.3. To define systemic relation of Servicer and Client operation.
2.4. To implement the components of the framework in a computational tool for simulation.
2.5. To test the tool for different simulations/cases of servicing.

1.3 Thesis Structure

The thesis is organised in independent chapters, the content of which has been published individually in separate journal papers and conference proceedings.

The current chapter presents the overall motivation and aim of the thesis, followed by the main objectives. In this chapter is also presented the thesis structure and novelties.

The main initial discussions and contextualisation about On-Orbit Servicing as well as the related literature are presented in Chapter 2. It presents a general review of the main developments in servicing to date as well as the top-level challenges and advantages expected for this area. In this chapter, the objective tasks 1.1, 1.2, 1.3 and parts of task 1.4 are presented.

Chapter 3 is dedicated to a systematic analysis of servicing, exploring the gap identified in the literature. This chapter is organised in a way to explore the two main sides of servicing, pointing to the main problem to be approached in the thesis. This chapter covers the tasks 1.4, 1.5, 1.6, 1.7 and 1.8, from Objective 1.

In Chapter 4 are presented the problem statement and the main proposition for its solution. This chapter brings specific contents of papers published throughout the research, summarizing the main solution proposed by this thesis.

Chapter 5 is dedicated to the detailed definition of the mathematical background of the framework proposed. The general concepts of operation of servicing and features expected for servicing applications are modelled and discussed through this chapter, including the verification and demonstration of the main studied parameters. Tasks 2.1, 2.2, 2.3 and 2.4 from Objective 2 are completed in this chapter. In addition, this chapter presents the part of task 2.5 (Objective 2).

In Chapter 6 the framework is explored as a guideline of how it is expected to be used in real-case scenarios. Different types of servicing are simulated for a given satellite fleet, under requirements and parameters observed in the current commercial servicing in the industry. Task 2.5 is complemented in Chapter 6 with examples of use of the framework.

In Chapter 7 the main current interests observed in the industry are cross-checked against the framework. Use cases are selected to demonstrate the framework capabilities and to present the assessment based on each case regarding the adoption of servicing. Task 2.5 and Objective 2 are completed in Chapter 7. By this chapter, the main objectives outlined for the thesis are met.

Chapter 8 is dedicated to discussing the main findings of the thesis, summarizing and expanding the contents discussed in the previous chapters. The limitations of the framework are discussed, analysing how upcoming research could continue from this point. The thesis concludes also in Chapter 8, highlighting the achieved objectives and the summary of contributions. Supporting material is provided in the Appendices.

1.4 Novelty

This thesis intends to establish the relationship of Client and Servicer in On-Orbit Servicing from a systems and concurrent engineering approach. As novel contributions, the following points are highlighted.

- A framework to explore the Servicer-Client relationship in On-Orbit Servicing.
- The concurrent approach to considering Client and Servicer points of view.
- Definition of technical and financial metrics to enable a more encompassing analysis of servicing.
- Standardised characterisation of different servicing applications and capabilities for current and future operations.
- Parameters to assist during the decision-making process towards servicing.

- Demonstration of the developed framework in scenarios relevant to the current and future development of space systems and activities.

2 Literature Review

This chapter presents an overall background of On-Orbit Servicing and the related research to date. The two main outputs of this chapter are the proposition of the taxonomy for On-Orbit Servicing and the identification of the current gap in the knowledge. In the following chapters the additional or specific literature and references covering the main subject of each chapter is presented as necessary.

2.1 Historic Overview

The concept of orbital servicing operations was initially used by Ehricke [1] as a controlled change of conditions (configuration and motion) of a technical system in space. Later Cepollina and Mansfield [2] addressed the use of the Space Shuttle to manipulate modular systems in orbit as a way to achieve extensions in lifetime, upgrades and improvements for satellites. Since then the research related to the different disciplines of servicing has been increasing as illustrated by Figure 2-1 [2], and a range of definitions have been established by different authors:

- NASA [3]: Repair, refurbishment, replenishment of consumables and assembly of systems in orbit.
- Waltz [4]: Replacement of consumables of a spacecraft; Systems and sub-systems assembly/construction or fabrication in orbit; emergency and scheduled maintenance of a spacecraft.
- Sommer [5]: Spacecraft in-situ observation, repositioning/re-orbit (by the use of a Servicer), manipulation. (Motion, Manipulation and Observation)
- Kreisel [6], Ellery [7], Flores [8]: Replenishment of consumables, upgrade, repair and assembly of systems in orbit.
- Kosmas [9]: A service vehicle for performing an in-space operation on a selected target spacecraft. (For robotic servicing)

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[2] The search criteria used in Scopus for the generation of the timeline of publication is the following: “on orbit servicing”, “in orbit servicing”, “on orbit assembly”, “in orbit assembly”, “satellite servicing”, “satellite refuelling, “satellite refuelling”. Results limited to conference and journal papers published until December 2017.

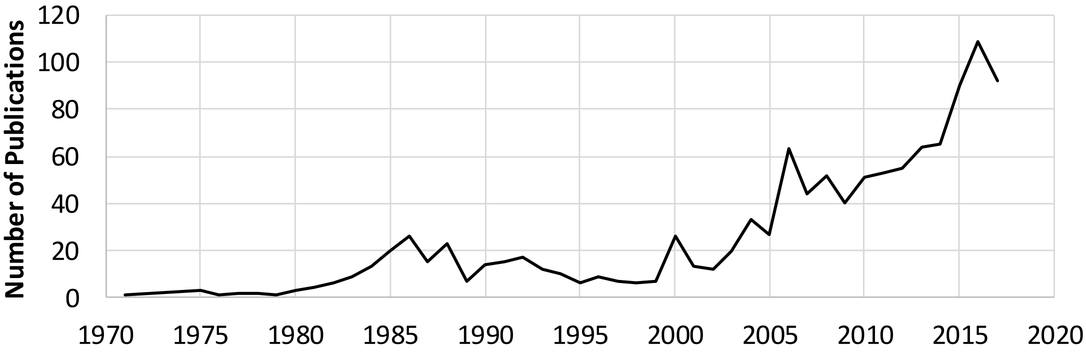


Figure 2-1 – Timeline of publications related to OOS

Although it could be difficult to individually track the reason for the peaks in Figure 2-1, possibly representing different relations of cause-consequence in the context of space missions at that time, some of them can be suggested. Around the beginning of Shuttle activities in 1981 more interests in using the Shuttle as main driver for servicing could explain the raise in the number of publications. Later interruptions due to accidents with Challenger and Columbia, respectively in 1986 and 2001, and the return of flights using Shuttle could be used to explain the oscillation in the number of publications and interests in OOS. The dependence of OOS upon other programs and missions is discussed in Chapter 3.

Servicing executed by astronauts marked the first examples of OOS during missions [3] such as Solar Maximum (1984), Westar-6 (1992) and Hubble (1993-2005). The implementation of OOS using humans has always presented attractive points mainly related to the dexterity and capacity of adaptation. However, the risks, complexity and costs as well as the current access to orbit are major drawbacks that make manned servicing less practical. Still, it is important to mention the most relevant example of consecutive, and ongoing manned servicing that is the International Space Station, in addition to the missions presented before.

With the attention turning to robotic servicing, technology demonstrators such as ETS-VII [10], Orbital Express [11] and RRM [12] paved the way to the current state of servicing missions and systems. Today, a significant expertise is available in space robotics, autonomous systems and serviceable satellites [8,13–15]. As an example of this knowledge, Figure 2-2 shows a timeline with developments of systems and spacecraft aimed at robotic OOS.

The figure summarises not only concepts of spacecraft and systems that were demonstrated or operated in a relevant environment, but also studies and concepts that did not achieve operational phases. In parallel with this timeline, the above-mentioned cases of manned servicing are included for contextualisation.

The spacecraft and systems presented in Figure 2-2 are detailed in the next chapter for the discussion about the technology and implementation issues of OOS.

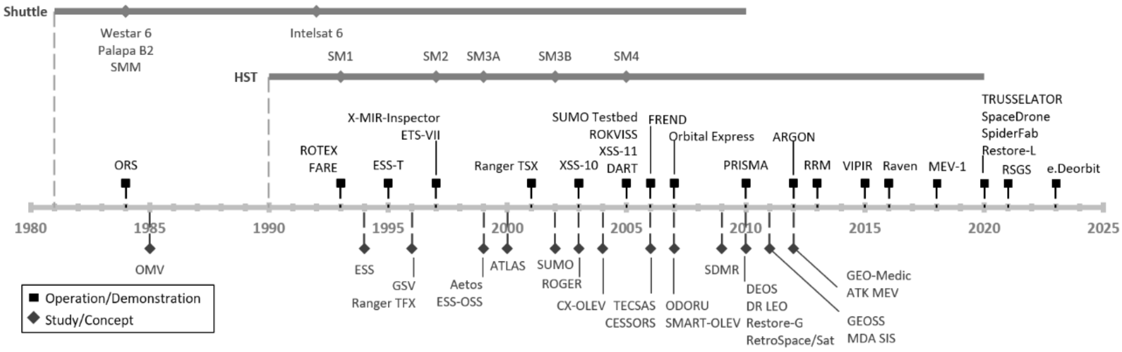


Figure 2-2 – Timeline of Missions and Systems dedicated to OOS

2.2 Servicer and Client

Robotic servicing consists primarily of two systems, the Servicer satellite performing all the tasks (e.g. refuelling) and the Client satellite receiving all the servicing tasks.

A significant number of concepts and research related to the Servicer system is currently available as presented by Flores-Abad et al. [8], Gefke and Reed [16], Kelm et al. [17] and Sommer [18,19]. The Servicer consists of a satellite bus with the addition of robotic payloads for servicing tasks. Such systems can also have different vision and navigation systems and range from tele-operation to total autonomy cases. The history of developments dedicated to OOS is illustrated in Figure 2-2 and detailed in Table 3-3 and Table 3-4.

The Client side can have a broader field of architectures. It can range from a conventional monolithic satellite (e.g. GEO communication satellite), to highly modularised systems to be assembled in space by a Servicer. Being so, the research related to the Client can be less consistent with major groups focusing on the modularity [20], plug-and-play [21], change of systems condition in space [22] and overall assembly in orbit [20,23–25]. One of the reasons for the dispersed research related to the Client lies on the fact that, beyond its architecture, its serviceability is dependent on the Servicer side. Client, Servicer and their mutual dependence are discussed in detail in Chapter 3.

2.3 Definitions and Taxonomy

From the systematic literature review, a standardised definition and taxonomy of OOS can be presented. Considering that some of the definitions can be confused with similar names from other areas, a full glossary is provided in Appendix A. The general top-level definitions are presented in Table 2-1.

Table 2-1 – On-Orbit Servicing Definitions

OOS Definitions	
Application	Different categories of servicing (Table 2-2).
Function	Specific action/task to accomplish the objective of a system/mission.
Servicer	Satellite responsible to execute tasks from each servicing application.
Client	Satellite being serviced or assembled by the Servicer.
Operator	Entity/people/organisation in control or operation of either Client or Servicer.

The main denominations for OOS presented by Waltz [4] and Kreisel [6] have been widely used and derived to define servicing in areas of Inspection, Motion and Manipulation. Additionally, concerns with space debris mitigation and remediation [26] have derived space applications, such as Active Debris Removal (ADR) [27], which can be included in the context of OOS. The definitions of main servicing applications as they are used in this work are presented in Table 2-2.

Table 2-2 – On-Orbit Servicing Applications

Application	Definition
Inspection	Servicer performing inspection of a Client in space via close formation or docked operation.
De-orbiting	Servicer performing the removal of debris/Client from the operating orbit and insertion into an atmospheric re-entry trajectory.
Re-orbiting	Servicer performing the removal of debris/Client from the operating orbit and insertion into the graveyard orbit.
Lifetime Extension	Servicer assistance for station keeping or correction manoeuvres after depletion of a Client's propellant or when depletion is imminent.
Rescue and Recover	Servicer responding to Client failures related to orbit insertion and mechanisms deployment or failure.
Maintenance and Repair	Servicer performing the upgrade of subsystems/parts, renewal of expendables or repair of failed subsystems/parts in the Client.
Repurpose	Servicer performing the salvage of subsystems/parts for reuse in a different objective for the Client operator or for a different operator.
Assembly	Servicer providing the on-orbit assembling of the Client satellite using pre-assembled/manufactured subsystems.

The main reason for the proposed definition is the functional arrangement of the servicing tasks that will be presented and discussed later. The comparison of the applications used in this work with other definitions in the literature is presented in Appendix B.

Servicing applications tend to overlap some of their tasks or activities, making it difficult to define or separate between applications. Therefore, the definition for each application presented herein does not intend being absolute or replacing any previously used definitions. The main objective of the presented definitions is to allow the further breakdown of servicing applications based on the main tasks performed during the operation.

Although some applications could have more emphasis in the operation of Geostationary/Geosynchronous satellites, servicing is virtually applicable to any space environment assuming a Servicer satellite could reach and service a Client satellite.

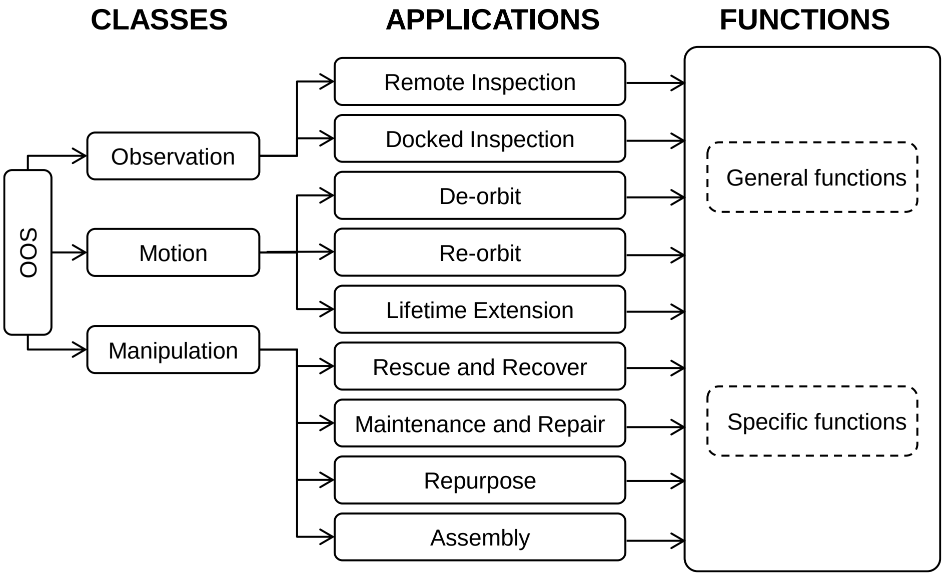


Figure 2-3 – OOS Functional Taxonomy

From the definitions presented in Table 2-2, a basic taxonomy is outlined in Figure 2-3. The main principles underlining this taxonomy are:

- To allow a common understanding of OOS from both Client and Servicer via the systematised categorisation.
- To assist in the requirement definitions and analysis.
- To anticipate the structure of possible outcomes of choosing servicing regarding its technical and implementation matters.

The lower level of this taxonomy focuses on the actions of servicing; therefore, functions were chosen as a categorisation method. A high level functional decomposition of OOS (Figure 2-4) presented by NASA [3] is used. This allows the later definition of the servicing functions which will be presented in the following chapters.

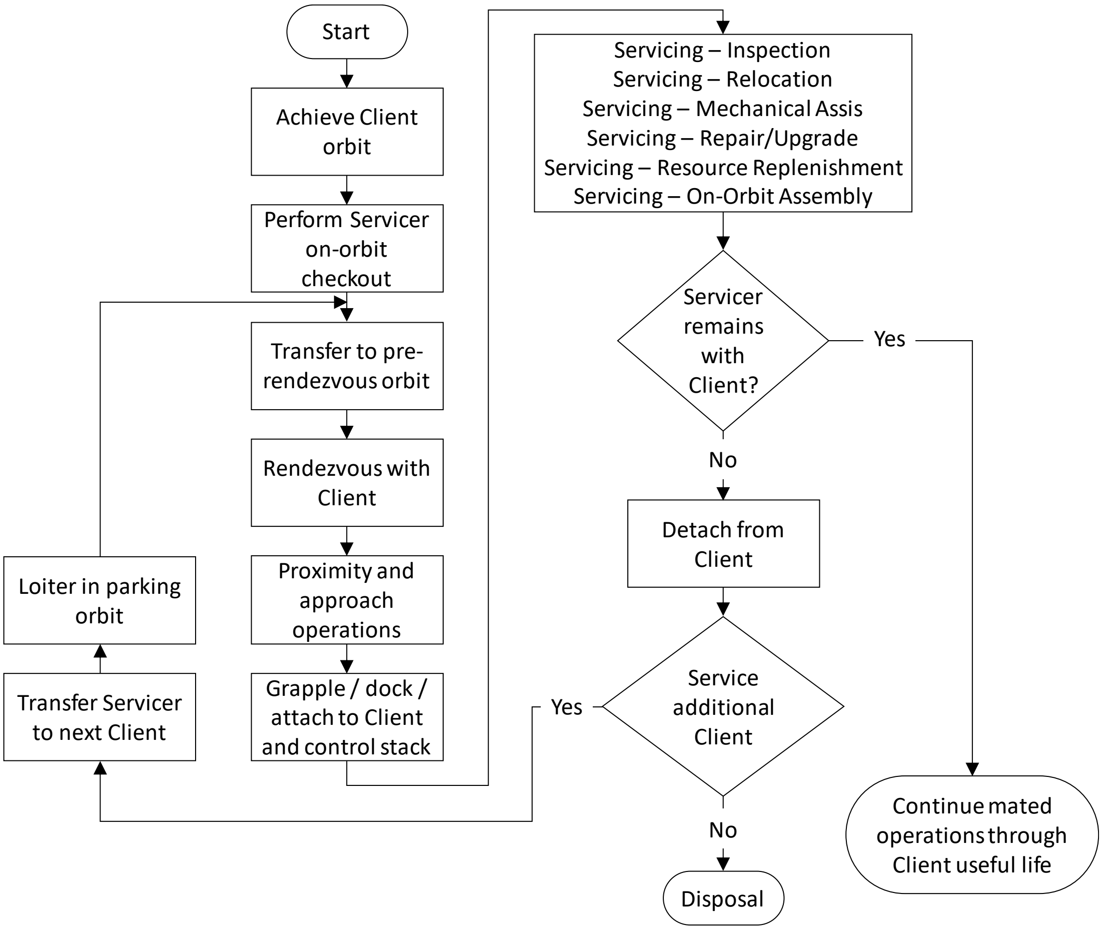


Figure 2-4 – Concept of Operation and Functional Decomposition – Servicer perspective – Adapted from NASA [3]

2.4 Advantages of OOS Applications

Although the advantages of using OOS solutions can be subjective to an operator or application, the following points cover the most evident areas discussed in the literature about attractive points of OOS.

The initial ideas related to OOS in the 1980's envisioned the creation of large infrastructures in space with an ambitious timeline as the main advantages [4]. Since then visions related to OOS matured with more consistent niches of applications and advantages.

The following points covering the advantaged of OOS encompass different technologies with a range of readiness levels. Thus, it is difficult to present a solid TRL for each of the areas/applications. With exception of cases of *Improvement and Upgrades*, all the other points have been at least demonstrated at some extent by individual subsystems or a technology demonstrator. Later, in Chapter 3 the different technologies related to servicing applications are presented. A range of TRL's observed in the literature is presented, allowing a better understanding of the readiness of each technology and, consequentially, each application.

Extension of life

A Servicer is used to extend the life of a Client satellite by tugging, pushing or refuelling it. This case deals with the propulsive capacity of the satellites, defined in terms of achievable change in velocity, ΔV. Such capacity is one of the main parameters in the definition of a space system architecture, desired orbit and lifetime. When tugging/pushing, the additional life is achieved with the Servicer in charge of attitude control, manoeuvres or station keeping of the Client for the required amount of time. When refuelling, the extension of life is achieved by the propellant transfer from the Servicer to the Client. The extra life provided by OOS could represent financial or operational advantages to a system with enough operational capacity [28]. This could be closely connected to strategic factors or changes in the market, representing an important option for operators.

Improvements and upgrades

A Servicer is used to improve, upgrade or augment the Client capacity. For this type of servicing, it is necessary that the Client satellite provides the compatibility for interchangeable sub-systems or additional electro-mechanical interfaces. The improvement/upgrade of the Client capabilities has been one of the main rationales for servicing and, today, it is mainly represented by the use of hosted payloads [29–31]. Hosted payloads are commonly referred as an additional payload/subsystem attached to a main system, using the satellite's space and spare resources to operate in a secondary mission. Persistent platforms also can be highlighted as another related technology. In this case, the satellite has a modularised architecture, with its main primary subsystems lasting for a longer time and subsystems such as payload replaced through the operational life. Having a system upgraded through the operational life can represent a better use of the system capacity and better response to the changes in the final user needs. Additionally, a baseline architecture capable of being upgraded through the life can also represent different re-arrangements of the systems budgets for mass, power and consequentially costs.

Response to failures

A Servicer is used to perform corrections to a Client failure such as mechanisms or other serviceable failures [15]. Such application demands extra dexterity of the Servicer depending on the complexity of the failure, as well as “serviceability” or accessibility to sub-systems in the Client architecture. The convenience of having a Servicer available to respond to a failure can represent a more flexible design philosophy of space systems. Considering today’s factors such as redundancy of subsystems and interfaces as well as factors related to reliability and insurance of a system, OOS could introduce more leverage in the design, procurement and operation [15].

Assembly

A Servicer is used to assemble pre-integrated systems in orbit. Such case is commonly taken as the main use of OOS. The possibility of creating systems in orbit, that otherwise would not be possible to launch due to mass and dimension constraints (e.g. large space telescopes [32]), represent a new range of capabilities for space missions. Orbital assembly overlaps with other areas such as on-orbit manufacturing [33] and in-situ resource utilisation (ISRU) [34,35]. The design philosophy behind on-orbit assembly can diverge drastically from the current systems, for which the launch phase is the main critical constraint driving its design.

Active Debris Removal

The current issues of space debris require policies to define mitigation [36] and remediation [26] measures to space activities. Complying to remediation plans, the use of a Servicer spacecraft to capture satellites and other large debris, e.g. upper stages, is one of possible solutions within Active Debris Removal (ADR) [37–39]. Although still not completely clear about the overall benefits, OOS systems performing ADR could bring advantages to the system design (mass allocation), as well as operational and insurance benefits for the Client operator. In a context with a legal framework properly defined for ADR, this could represent a new market related to space sustainability [40,41] which is already suggested by proposed commercial cases [42].

2.5 Challenges of OOS

In parallel with the advantages, the implementation of servicing solutions has been faced with different challenges. Some of these challenges are covered by other authors specifically regarding operations (Sellmaier et al. [43]) and technical and economic feasibility (Sullivan [44]). Since the challenges of OOS have been discussed extensively, some of the points discussed can be presented with immediate solutions suggested to overcome it.

Parallel development

The context of servicing in the early 1980's focuses on the use of the Space Shuttle as the main driver to enable a space infrastructure. It was at that point that programs such as the Space Assembly, Maintenance and Servicing (SAMS [4]) were outlined. Since then, it is possible to identify periods of interest in servicing by checking the number of research publications related to OOS subjects (Figure 2-1 and Figure 2-2).

From Figure 2-2, it is possible to observe a peak in the number of publications after the beginning of Shuttle activities and the first manned servicing on Solar Maximum Mission (SMM), Palapa and Westar [3]. This suggested relation could be used to discuss the dependency of OOS on other programs. The accident on the Challenger

(1986) followed by a brief interruption on shuttle activities also exemplifies this apparent relation since a smaller number of OOS research publications was produced in the following years. However, more recently, it is observed an increase in the publications and apparent interests in servicing even after the end of Shuttle operations. Although this could be also driven by the development of new concepts dedicated to servicing, the dependency on parallel developments does not seem to limit the development of servicing anymore.

Unreliable or technical immature technology

From what can be observed in the previous developments (Figure 2-2), the different technologies necessary to servicing exist with different levels of maturity or readiness. Basic applications of servicing were demonstrated, accumulating knowledge and heritage, and today are presented with enough maturity for implementation. Furthermore, spin-offs from general space applications performing the same or similar functions also contributes to the general technological maturity. Regarding the reliability, the only current parameter to access a servicing system (as a whole) is the previous heritage on that system. Therefore, estimating how reliable a servicing system can be, depends not only on the concept of operation but also on the expertise of the operator proposing such system.

The dependence of servicing concepts on the Client side is an important aspect to understand the reliability of different OOS concepts and to estimate and improve the technological maturity. A detailed discussion about this maturity is presented in Chapter 3.

Potential market and servicing profitability

The potential market is closely related to the previous point; operators are not keen to move towards concepts with low or no heritage. As the research today pushes the maturity to applicable levels (e.g. TRL > 7 – successful demonstration of performance in the relevant environment) and demonstrates the benefits of servicing, companies have begun to openly express interest in OOS. Discussions between companies regarding Requests for Information (RFI's), cooperation in servicing concepts and the signature of servicing contracts exemplify the increasing market for servicing.

- DARPA + SSL: Currently developing Robotic Servicing of Geosynchronous Satellites (RSGS) [45], Phoenix Project [46] with results from the Orbital Express [11] and DEXTRE [47]. Seeking for commercial operators to partner and demonstrate/implement servicing solutions [48].
- Orbital ATK: Currently developing the Mission Extension Vehicle (MEV) for rendezvous and docking with a Client satellite providing attitude control and propulsion [49]. A recent contract signed with Intelsat [50] shows the interests from the Client side.
- Effective Space Solutions: Currently developing a Servicer for station keeping and orbital manoeuvres [51]. Recently a letter of intention was signed by a confidential satellite operator to receive services for lifetime extension.
- Airbus DS: Demonstrated capability to develop and operate a space-tug system based on the expertise in Europe for rendezvous and docking, robotics and propulsion. One proposed service is to use a space tug to deliver satellites to the end orbit as a way to explore new space logistics to launch and operate satellites [52].
- Astroscale: Currently developing Servicer systems for ADR under a commercial perspective [42].
- SES and Intelsat: Currently interested in servicing for future assets to be incorporated in its fleet. The negotiations with SSL and ATK are focused on provide refuelling, extension of lifetime and payload replacement. [53].

This highlights that, while different from what was expected at the beginning of OOS plans, there is a potential market. From the examples cited before, the following missions (Table 2-3) are expected to be launched for commercial operations within the next five years.

Table 2-3 – Commercial Servicing Operators

Servicer System	Servicer Operator	Client Operator	Method	Launch	Ref.
MEV-1	Space Logistics	Intelsat	Life Ext.	2019	[50,54]
SpaceDrone-1	ESS	Undisclosed	Life Ext.	2020	[55]
Restore-L	NASA	NASA/Landsat	Refuel.	2020	[56]
RSGS	SIS	SES	Life Ext. + Refuel.	2021	[45]
Space Tug	Airbus DS	Undisclosed	Life Ext. + Maint.	N.A.	[57]

Together with the technical capability and potential market, there is the challenge of making servicing profitable from both Servicer and Client points of view. Considering standard satellite design processes, servicing can be presented with challenges to offer a profitable solution.

Cases of life extension and response to failures are options for satellite operators whether their assets are designed with focus on servicing or not. From the Servicer perspective, such applications are presented with enough maturity for basic operations in space (the detailed assessment is presented in Chapter 3). In reality, *Lifetime Extension* and *Rescue and Recover* have potential to increase the profitability as discussed in the literature [6,28,58–61]. For example, Ellery et al. [58] discusses how systems' high reliability, system failures and OOS design philosophies provide commercial opportunities for a space-based industry. Similarly, Graham [60] expands upon the benefits of using recovery strategies based on OOS in large commercial fleets Saleh et al. [59] covers on decisions related to whether reduce or expand the satellite lifetime and, for the later, how servicing could be used. The repurposing of satellite components and the economic implications of doing such tasks are presented by Banhart and Sullivan [61].

Still, the profitability is not a challenge completely solved as it involves understanding the particularities of the relation between Client and Servicer. Hastings et al. [62] discuss the insertion of OOS in the "space enterprise", directing to points related to cost of servicing and effective incorporation of servicing solutions in the Client system. Such points encompass Client and Servicer and highlight the need to explore their relation.

Cost centric and value centric views

Another challenge related to the effective implementation of OOS is the general cost-centric view. Such view summarises the challenges presented, making the satellite operator reluctant to choose servicing because of the idea that it would cost more due to less maturity, and a lack of options of servicers for operation. Being a novel solution, the use of a cost-centric view/approach can present the development of Servicers and Clients as costly. Factors such as maturing the technology (TRL), manufacturing and integration of first unit [63], and the risks involved (de-risking) have direct influence over the costs of satellites adopting new solutions.

As discussed by different authors [64–67], a value-centric approach allows the exploration of the value of servicing solutions and a trade-off with the costs for developing, especially in the beginning when such solutions will cost necessarily more.

In practical terms, both views are exemplified as follows:

- Cost Centric View: A commercial operator aiming for financial benefits in the operation of its system. Thus, the use of servicing solutions should represent potential profits, for example, if compared to a conventional satellite operation without servicing.
- Value Centric View: A non-commercial operator (e.g. science) aiming for improvements in their system by using servicing. Although cost/value is necessarily related to the servicing of this system, the ways of assessing the benefits of servicing would be different. For example, in a science mission value is likely related to the technical performance in generating science data.

Legal and political framework

Perhaps one of the most challenging points today regarding OOS is related to the legal and political implications of using it. Such points have been discussed for a range of factors including regulations, licensing, information exchange and policy framework (Hastings et al.[62], Losekamm et al. [68], Belcher et al. [69]). Other concerns to be considered regard the unsolicited intervention or servicing, or the militarised use of servicing capabilities and ownership of resources in space. The first steps towards a common ground for servicing use and good practices can be exemplified by a current consortium (*Consortium for Execution of Rendezvous and Servicing Operations* – CONFERS) led by DARPA, encompassing major industry and research groups [70]. Still, the discussions related to legal and political challenges are expected to progress and mature as more commercial cases of servicing are proposed and operated.

2.6 The "big three"

Although Waltz [4] can be dated regarding some of the concepts and applications of servicing, the points discussed on how OOS should be approached can be re-visited based on the current stage. Waltz discusses about how to incorporate servicing into spacecraft's early design and summarises:

1. *"The spacecraft design process must employ the system engineering disciplines to match the serviceable spacecraft design requirements to the interfaces and capabilities of the servicer system, and to negotiate as much customer friendly options as possible into the servicer hardware.*
2. *Modularity and standard interfaces are the key to serviceable spacecraft design.*
3. *Serviceable spacecraft may offer an affordable option to satellite replacement.*
4. *Technology readiness, user needs, and economics are the "big three" influences on the decision to incorporate servicing into spacecraft design."*

From the observed research, large groups concentrate on the individual developments of Client and Servicer regarding their own architecture, operation and modularity. The exploration of the summarised points in a way that Client and Servicer are put together is still a research gap that has not been explored.

The "big three" are points that are still relevant today for the inclusion of OOS as a recurrent option in the design and operation of space systems. Different research areas have been exploring independently/individually TRL, user needs and economic aspects of servicing but there is still a gap related to the integration of all those points in the OOS context.

2.7 Summary

This chapter presented the general literature review related to OOS, with focus on the robotic servicing. Based on the review of OOS the following aspects are observed:

- Robotic servicing shall be addressed separately from manned servicing in this research. Servicing using astronauts is acknowledged to continue to be performed but such activity regards primarily to the areas of manned flights and crew safety for EVA.
- The range of definitions/denominations for servicing activities is not standardised and varies based on each research focus. A standardised definition based on the recurrent denominations allows the common understanding of the area.
- The taxonomy proposed assists in the standardisation process from a systemic point of view. However, such taxonomy can be specific to the objective of a study so, herein, the main functions of OOS are used as the lower level of categorisation.
- The functional decomposition highlights the incremental characteristics of OOS. Functions for less complex servicing applications are a necessary step to implement more advanced servicing applications such as those suggested in the 1980’s.
- The previous dependence of OOS on mainstream programs illustrates the hiatus in the research and development right after the first OOS propositions. However, the increase in research and development programs during the last 10 years suggests OOS now as a dedicated/independent area.
- There is a current interest and trend towards using OOS with a commercial perspective for applications of less complexity such as *Lifetime Extension* and *Maintenance and Repair*.

The points discussed related the advantages and challenges share common aspects regarding the necessity of understanding the link between the two sides: Client and Servicer. The advantages for either of the sides influence directly the challenges of the counterpart. However, this link is not a major area of current research. Servicer systems have been the focus of research followed by a less frequent focus on the research on Client serviceability. Mostly no work on the relation between Servicer and Client is available. To explore this gap, in the next chapter a detailed analysis will be presented based on the review of the literature.

3 Exploration of System-level Issues of OOS

This chapter expands upon the findings of the Literature Review with content directed to the analysis of concepts and stakeholders related to OOS. The objective of this chapter is to provide a systemic organisation of the top level of OOS issues, linking it with the Research Aim and Objectives presented in Chapter 1.

The two main sides of OOS are discussed. First the Servicer side is presented with the background of related missions and systems, allowing then a functional analysis. The Client side is discussed regarding the different stakeholders and their individual concepts of operation and evaluation of their systems, providing then a general understanding of how OOS can affect their missions.

3.1 Servicer

In this section, the Servicer side is analysed looking at two main points, the servicing technology and the implementation of a servicing mission.

3.1.1 Technology

From the technology standpoint, Servicer systems and subsystems have been explored in detail as it was presented in the previous chapter. The taxonomy presented allows a more specific view of the stage of this technology regarding the applicability. The current technology can be arranged in two main groups.

1. Technology coming from parallel missions not dedicated to OOS
2. Technology developed exclusively for OOS

The functional decomposition presented in Figure 2-4 is used to outline the high-level functions for OOS. It is important to note that as servicing systems become more complex or encompass a different range of applications, the functions become more specific. The objective of the functions presented in Table 3-1 is to capture the most primary tasks to be considered by the Servicer. The table also presents a categorisation to indicate whether the function is from an OOS context or if it is observed in general space developments. For cases when the Technology Readiness Level [3] [71] (TRL) identified is not TRL 9, a range of minimum and maximum observed TRL is presented. Since the technology selected to execute a given function can vary depending on the mission or stakeholder, the TRL presented here is used as a figure to evaluate the general domain of these functions. Also indicated are the functions which require direct Client cooperation.

Table 3-1 – OOS High level functions

ID	Function	Category	TRL	Remarks
F1	Achieve/Keep Orbit	General	9	-
F2	Check Systems	General	9	-
F3	Rendezvous Far-Range	General	9	-
F4	Rendezvous Close-Range	General	9	-
F5	Recognise Client	Specific	7 – 9	Demands Client cooperation
F6	Berth	Specific	9	-
F7	De-berth	Specific	9	-
F8	Dock	Specific	9	-
F9	Undock	Specific	9	-
F10	Control Attitude	General	9	-
F11	Control Dynamics	Specific	5 – 9	Demands Client cooperation
F12	Handle Client	Specific	7 – 9	Demands Client cooperation
F13	Recognise System/Part	Specific	6 – 9	Demands Client cooperation
F14	Handle System/Part	Specific	7 – 9	Demands Client cooperation
F15	Telepresence	Specific	9	-
F16	Teleoperation	Specific	9	-
F18	Store ORU	Specific	4 – 9	Demands Client cooperation
F18	Transfer Fluid	Specific	7	Demands Client cooperation
F19	Burn/Ignition	General	9	-

A similar set of functions can be identified in the development the general space systems and missions. The long heritage of autonomous rendezvous, docking and the associated functions is observed in the following examples:

- *Progress, ATV*: Autonomous manoeuvring, rendezvous and docking
- *HTV, Cygnus CRS, SpaceX CRS*: Autonomous manoeuvring, and rendezvous

---

[3] The definition of Technology Readiness Level used herein follows the European Cooperation for Space Standardization (ECSS) guidelines.

- *Canadarm 2*: Target recognition, manipulation, Orbital Replacement Units manipulation and fluid transfer
- *JEMRMS*: Target recognition, manipulation and Orbital Replacement Units manipulation
- *SPDM*: Target recognition, manipulation and Orbital Replacement Units manipulation
- *TORU*: Target recognition, manipulation and Orbital Replacement Units manipulation

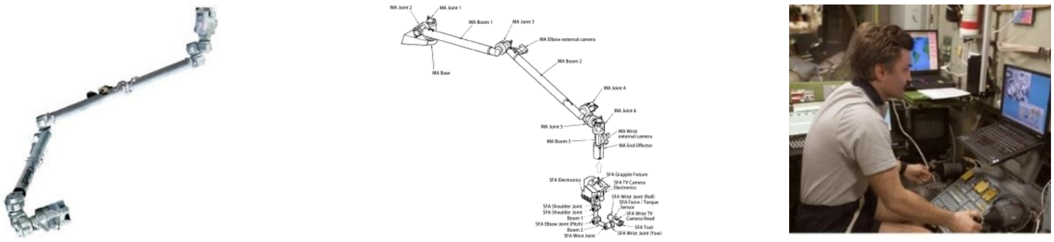
(a) ATV and Progress [72]

(b) SPDM (DEXTRE) [73]

(c) HTV [74]

(d) Cygnus [75]

(d) Dragon [76]



(e) Canadarm 2 [77]

(f) JEMRMS [78]

(g) TORU [79]

Figure 3-1 – Examples of complementary spacecraft and systems

Other different space missions may also present functions relevant to servicing such as OSIRIS-REx [34,80], Rosetta [81], Hayabusa [82,83]. For subsystems and spacecraft/satellites developed exclusively for OOS a list is presented in Table 3-3 and

Table 3-4. In addition to categorisation in the higher level of the taxonomy, it is also presented the project phase achieved based on the European Cooperation for Space Standardization (ECSS) life cycle phases [84]. The project phases are presented in Table 3-2 for reference.

Table 3-2 – ECSS Project phases

Phase	Definition
0	Mission analysis/needs identification
A	Feasibility
B	Preliminary Definition
C	Detailed Definition
D	Qualification and Production
E	Utilization
F	Disposal

Additionally, the high-level functions identified in Table 3-1 are associated to each concept in the table based on the information available in the literature. Although the information about such projects is limited to the publicly available information, a general picture can be defined based on the achieved progress by such projects, as summarised in Figure 3-2.

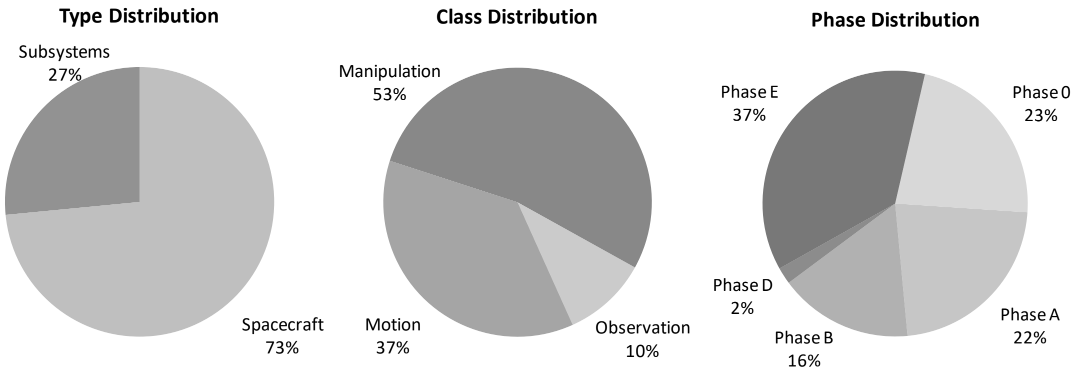


Figure 3-2 – Summary of developments exclusive to OOS

Table 3-3 and Table 3-4 highlights that, even though some of the observed developments did not achieve the operation phase, much of the critical knowledge related to OOS functions has been understood/achieved. According to ECSS [84], projects that reached phases beyond phase B should have defined in detail all the functions of the system. Meanwhile, projects at phases 0 and A usually would have the basic functions identified without further refinement. A more detailed content of the subsystems and spacecraft in Table 3-3 and Table 3-4 is presented in a simplified database in Appendix C. This database was used at early stages of this research as part of the main tasks defined for the first research objective.

Table 3-3 – History of Servicer Concepts – Spacecraft and Subsystems (Part 1 of 2)

Concept	Type	Class	Function ID																			Phase	Ref.
			F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19		
ORS	System	Ma	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	E	[85,86]
OMV	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-	-	-	1	1	B	[4]
FARE	System	Ma	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	E	[3,87]
ROTEX	System	Ob	-	-	-	-	-	-	-	-	-	-	-	1	-	1	1	1	-	-	-	E	[88]
ESS	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	1	0	[89]
ESS-T	System	Mo	-	-	1	1	1	-	-	1	-	-	1	-	1	1	-	-	-	-	-	E	[90]
Ranger TFX	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	1	1	1	1	1	-	1	A	[91]
GSV	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	1	1	-	1	1	-	-	1	B	[92–94]
ETS-VII	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	1	1	1	1	-	-	1	E	[95,96]
MIR-Inspector	Spacecraft	Ob	1	1	1	1	1	1	1	-	-	1	-	-	1	-	1	-	-	-	1	E	[97]
ESS-OSS	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	1	-	-	-	-	-	-	1	0	[98]
Aetos	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	-	-	-	-	-	1	1	A	[99]
ATLAS	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	-	-	1	1	1	-	-	A	[100]
Ranger TSX	System	Ma	-	-	-	-	1	-	-	-	-	-	-	1	1	1	1	1	1	-	-	E	[101]
SUMO	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	A	[8,102]
ROGER	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	1	A	[103,104]
XSS-10	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	-	1	1	-	-	-	-	-	E	[105]
CX-OLEV	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	1	-	1	1	-	1	1	B	[106–108]
XSS-11	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	-	1	1	-	-	-	-	-	E	[109]
DART	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	-	1	1	-	-	-	-	-	E	[110,111]
ROKVISS	System	Ma	-	-	-	-	-	-	-	-	-	-	-	1	1	1	-	1	1	-	-	E	[18,112]
SUMO Testbed	System	Ma	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	1	-	-	-	E	[113]
FREND	System	Ma	-	-	-	-	-	-	-	-	-	1	-	1	-	-	-	1	-	-	-	E	[114]
CESSORS	Spacecraft	Ma	1	1	1	1	1	1	1	-	-	1	-	1	-	-	-	-	-	-	-	0	[115]
TECSAS	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	1	-	-	1	1	-	-	1	B	[112,116]
SMART-OLEV	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	1	-	-	-	-	-	1	B	[117]
Orbital Express	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	1	-	-	1	1	1	1	1	E	[11,118]

Ob: Observation, Mo: Motion, MA: Manipulation

Table 3-4 – History of Servicer Concepts – Spacecraft and Subsystems (Part 2 of 2)

Concept	Type	Class	Function ID																			Phase	Ref.
			F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19		
ODORU	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	-	-	1	1	1	-	1	0	[119]
SDMR	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	1	A	[120]
PRISMA	Spacecraft	Ob	1	1	1	1	1	1	1	-	-	1	-	-	-	1	-	-	-	-	-	E	[121,122]
DEOS	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	1	1	-	-	1	1	-	-	1	B	[116]
DR LEO	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	-	-	1	A	[123]
RetroSpace/Sat	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	1	-	-	1	-	-	-	1	A	[40,124]
Restore-G/L	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	-	-	-	-	-	1	1	B	[3]
GEOSS	Spacecraft	Ma	-	-	1	1	1	1	1	1	1	1	1	1	-	-	1	-	-	-	-	0	[125]
MDA SIS	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	-	-	1	1	1	-	1	0	[126]
GEO-Medic	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	-	1	1	A	[60]
ATK MEV	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	1	-	-	-	-	-	-	1	0	[126]
ARGON	System	Mo	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	-	-	1	E	[127,128]
RRM	System	Ma	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	1	1	-	E	[12,16]
VIPIR	System	Ob	-	-	-	-	1	-	-	-	-	-	-	-	1	1	1	-	-	-	-	E	[16,129]
Raven	System	Ob	-	-	-	-	1	-	-	-	-	1	1	-	1	-	-	-	-	-	-	D	[127,130]
CleanSpace One	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-	A	[126,131]
Trusselator	System	Ma	-	-	1	1	-	-	-	1	1	-	-	1	-	-	-	-	-	-	-	0	[33,132]
SpiderFab	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	-	-	1	1	1	-	-	0	[33]
Phoenix	Spacecraft	Mo	1	1	-	-	-	1	1	-	-	1	1	-	-	-	-	-	-	-	-	B	[46]
e.Deorbit	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	-	-	1	A	[133,134]
ESS Tug	Spacecraft	Mo	1	1	1	1	1	1	1	1	1	1	-	1	-	-	-	-	-	-	1	0	[135]
Archinaut	Spacecraft	Ma	1	1	1	1	1	1	1	1	1	1	-	1	-	-	-	-	1	-	1	0	[136]

Ob: Observation, Mo: Motion, MA: Manipulation

3.1.2 Implementation

From the implementation standpoint, some aspects can be raised regarding Servicer missions and systems achieving the operation phase.

Most of the concepts from Table 3-3 and Table 3-4 that achieved the operation phase were technology demonstrators. Being so the operator had the control of both sides with the Client normally represented by a target system [10,11,105,110].

However, for cases beyond technology demonstration more participation of the Client is necessary. For this reason, functions that demand more Client cooperation can be limited in the demonstration of the technology. This can be noted by the range of TRL observed for the high-level functions of Table 3-1. Such technology can have a lower TRL as well as having a wider range of TRL observed depending on the specific technology used. This is due to different technologies (with different TRLs) being able to execute the same function, for example the capturing of a satellite using harpoons, nets or a robotic arm.

The implementation of a commercial servicing mission also highlights the importance of considering the Client side in the design process of the Servicer. Previous systems driven by the commercial perspective of OOS [106] failed to progress beyond the preliminary definition phases which can be linked to this dependence. Additionally, designing a servicing mission focusing on a single Client will hardly represent a commercial case for the Servicer operator. Commercially, the consideration of the Client by the Servicer encompasses more than the cost/price of a service. Driving such cost/price are factors of the logistics of the Servicer mission, the compatibility with a different range of Clients and OOS applications, scheduling and responsiveness.

Such aspects reinforce the findings in the review of the literature. Despite having most of the technology ready for certain applications, the lack of Client participation in the concretisation of the Servicer systems and subsystems can be an issue. The Servicer dependence on the Client side can affect directly:

- Definition of Concept of Operations
- Definition of resources and logistics

- Design and sizing of the system
- Mission design
- Implementation of the mission
- Implementation of business model

3.2 Client

This section focuses on the analysis of the Client side, looking at two main points, the servicing technology and the implementation of a serviceable system/mission.

3.2.1 Technology

The technology necessary for the Client serviceability is closely linked to the functions being performed by the Servicer. The association of the Servicer functions with the major subsystems of the Client is presented in Table 3-5. The table also shows a reference of project in which the specific function-subsystem combination has been described, demonstrated or is under research or development.

Table 3-5 – Client subsystems and Servicer function [a] relationship

ID	Client Subsystems	Servicer Function ID							Ref.
S1	Mechanical	F5	F6	F7	F12	F13	F14	F18	[20,137]
S2	GNC/AOCS	F1	F3	F4	F10	F11	-	-	[3]
S3	Propulsion	F18	-	-	-	-	-	-	[12]
S4	Electrical	F13	-	-	-	-	-	-	[137]
S5	Communication	F5	-	-	-	-	-	-	[3]
S6	Docking mechanism [b]	F8	F9	-	-	-	-	-	[24,138]
S7	Standard. and Modularity of Interf. [b]	F13	F14	F17	-	-	-	-	[24,137]

[a] Servicer function ID as presented in Table 3-1.

[b] Although S6 and S7 are part of mechanical and electrical subsystems, they represent an integration point of multiple subsystems. This can be observed by developments such as electro-mechanical interfaces [25] and hosted payloads [29,30,139].

This association is possible based on the technology demonstrators presented earlier. In summary, the technology necessary for the Client to be compatible with servicing exists but demands improvements. It becomes limited in options and maturity as the applications become more complex (e.g. parts/components swap).

Covering a range of more advanced servicing applications, specific technologies are currently in advanced development such as hosted payloads [29,30], refuel [138] and modular design and orbital replacement units (ORU) [25].

On the other hand, primary types of servicing (Observation and Motion classes) can be more flexible regarding the Client and subsystems compatibility.

According to the capabilities advertised for the current servicing systems (RSGS and MEV [45,140]), some OOS applications may not require a dedicated compatibility of the Client. For example, the capture of a Client by a robotic arm and docking/attachment can be performed using features currently available in the satellites such as the interface ring with the launcher.

Refuelling is another example generally considered, depending mostly on the Servicer capacity in manipulating attachments, valves and transferring fluids. However, the later function also encompasses characteristics of the propellant and pressuring to be completed.

The range of technologies to be considered by the Client is not limited to the addition compatible subsystems summarised in Table 3-5. Despite the current advancements of the technology from the Client side, the mutual dependence of Client and Servicer is a limiting factor as observed by the tables with functions and subsystems. Especially for well-established operators, such as commercial, the adoption of a new technology can be a complex process. The demonstration and validation of these technologies as well as the cost-benefit in using it are points satellite operators use to drive their procurement and design process to implement OOS solutions on the Client side.

3.2.2 Implementation

The implementation of a serviceable Client goes in parallel with the implementation of the Servicer.

As discussed before, not all types of servicing rely on a dedicated hardware implementation in the Client architecture. For these cases, assuming the Servicer would have the necessary technology and dexterity, the servicing operation would not demand an early commitment of the Client operator in the initial design phases. Still, the assessment of the benefits and challenges of servicing would be part of the decision process which will be discussed in the next chapters.

Analysing servicing applications regarding when the Client operators must start to consider servicing for their missions involves an overall look of the different phases of the project. The project phases and reviews defined by the ECSS project Life Cycle can be used to estimate when OOS would need to be considered by the Client operator depending on the OOS application.

Although there are no specific guidelines yet in ECSS regarding servicing, a reference point can be found using the guidelines for debris mitigation since some of these activities can overlap with Active Debris Removal (ADR). Activities of ADR will normally take place at the end of the mission, during the disposal phase (Phase F). In the design phases, the Debris Mitigation Plan needs to be issued together with other relevant documents at the end of phase B (Preliminary Design Review – PDR).

As servicing applications become more complex involving the development of dedicated subsystems as outlined by in Table 3-5, the main decisions regarding the implementation need to be taken at most in the Systems Requirement Review (SRR), for operations that will happen later during Phase E.

Going further in future OOS applications, the case of assembly of the entire system (satellite) demands the consideration since the first concept of the mission, in the Mission Design Review (MDR). Although the individual subsystems are expected to be ready to integrate, the final assembly of the system may only take place in orbit. This brings some interesting aspects and challenges of executing the Verification and Validation (Phase D) after the launch. However, this represents a general view of the case of assembly in space from the perspective of project management. As this application relies on the implementation of previous “least complex” types of servicing, the discussions regarding the implementation of on-orbit assembly are still in initial stages.

In Figure 3-3, Figure 3-4 and Figure 3-5 are presented the general schematics that can be drawn using the Client life cycle as reference to indicate the execution of different applications of servicing and their influence in the design. The colour/shade difference in the project phases indicate the main period of conception and design, and the phase in which servicing is expected to occur.

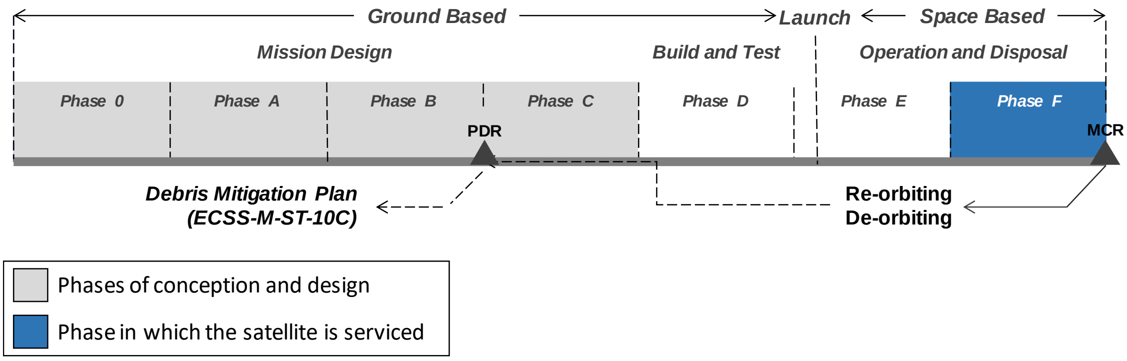


Figure 3-3 – OOS Influence over Client life cycle – De-Orbiting and Re-Orbiting

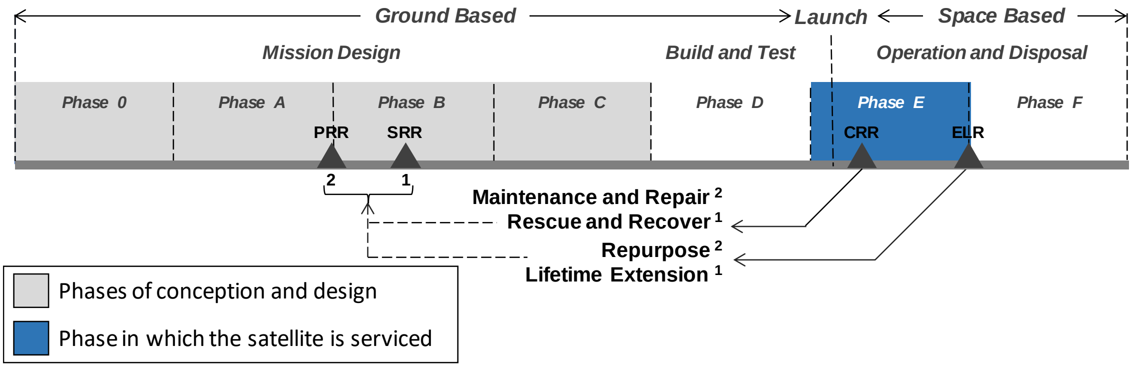


Figure 3-4 – OOS Influence over Client life cycle – Lifetime Extension, Rescue and Recover, Maintenance and Repair and Repurpose

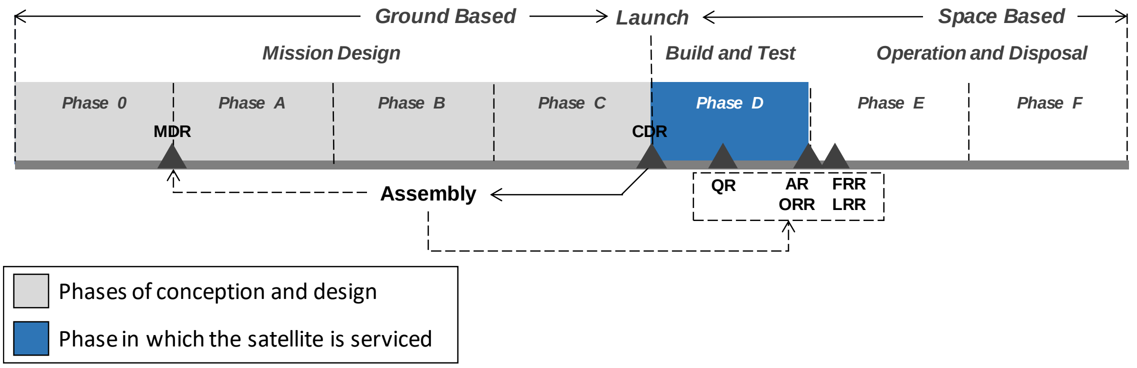


Figure 3-5 – OOS Influence over Client life cycle – Assembly

The points presented highlight how the implementation of servicing from the Client perspective can take place in different phases, emphasising the necessity of having a clear link with the Servicer side for the decision making.

Despite some of the technology being already available, the operators are faced with critical trade-offs if considering the implementation of OOS in their systems/missions. The adoption of a servicing technology without the guarantee of availability is a common discussed issue. Prior any decision regarding the adoption of servicing, Client operators would want to look for potential Servicer operators, exploring their offered services, availability and conditions. Examples of such interactions can be highlighted from recent cases involving SES and SSL [141], and Intelsat and Space Logistics [50].

Furthermore, the lack of a proper relationship with the Servicer side has direct effect in factors such as:

- Architecture/system redesign
- Interference in the operation
- Value assessment of the system
- Financial implications

Added to those points, different Client operators have their own ways of giving value to their systems and assessing the success or effectiveness of OOS. Here, the use of different Key Performance Parameters (KPP) [142,143] and Measure of Effectiveness (MoE) [142,143] add more complexity to the relation of Client and Servicer. Although the financial implications of servicing can be commonly used as driver for value appreciation, other technical/operational drivers such as flexibility, availability, reliability are examples of KPP’s and MoE’s to be considered in OOS.

The necessity to consider the technical aspects (e.g. architecture change and interference in the operation) and the value and cost implications for the implementation of servicing were concerns observed by the author during informal interviews and discussions with representatives of a large communication satellite operator. The informal discussions and interviews were protected against the disclosure of confidential information, however, general topics [4] regarding the concerns with the implementation of servicing solutions are presented as follows:

- Configuration of Servicer docked/attached to the Client and the interference over the Client operation.
- Conditions and characteristics of refuelling.
- Certainty/assurance of when the servicing operation would be performed.
- Charges for servicing operation and time of payment.
- Time for manoeuvres and servicing logistics.

From the Servicer side, similar concerns regarding the implementation of servicing were also observed by the author in informal discussions with representatives of Servicer operators during conferences (the author and representatives of Effective Space Solutions and SSL during the 69th International Astronautical Congress).

3.3 Summary

From the systemic analysis of Servicer and Client regarding the available technology and the implementation of OOS the following points can be summarised:

- The overall technology available from the Servicer side has enough maturity for missions of less complexity. Similarly, for the Client side no major technical developments would be necessary for the adoption of simple types of servicing.
- The implementation of Servicer missions has been demonstrated but not effectively verified in a real “servicing ecosystem” raising concerns from the Client side. The commitment of the Client at early phases of the design can be indicated as a major issue to allow such “servicing ecosystem”.

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[4] The detailed content of the topics was adapted/edited to protect the confidential information related to it.

Apart from scepticism or cautious views regarding servicing, the mutual dependence of Servicer and Client is a major issue for the use of servicing solutions. The lack of a proper link between Client and Servicer observed in the literature review affects directly the development of further technologies in OOS as well as the implementation for both Client and Servicer as demonstrated in this chapter.

The following chapter presents the problem statement based on the issues raised here and proposes a solution to be explored in the later chapters.

4 Problem Statement and Methodology

In this chapter are presented the problem statement, the proposed solution and its characteristics, concluding with the overall methodology adopted.

4.1 Problem Statement

The exploration of the systemic link between Client and Servicer in the context of On-Orbit Servicing should be part of the decision-making process for the design and operation of space systems.

In theory such systemic link could be individually explored from one side or the other. However, this process can consume a significant portion of the design and procurement phases and would be relevant to a limited number of cases. In a real-life scenario, the individual consideration of OOS involves translating of the information available about OOS into useful inputs for spacecraft design; a challenging task due to the variety of applications and possible interactions between both sides.

Added to other issues discussed in Chapter 3 regarding technology and implementation, these are the main reasons why exploration of the relationship between Servicer and Client is still non-existent in the design process of systems and missions.

4.2 Solution Proposition

The solution proposed herein focuses on the exploration of Client and Servicer relation in a systemic and concurrent way. To do so, the main approach adopted is that Client and Servicer have a common relationship link for the exploration of OOS concurrently. This Relationship Approach is implemented via a framework in which the issues discussed before are explored through their technical drivers in the system design and operation. The following sections describe in detail both items.

4.2.1 Relationship Approach

The main idea of the Relationship Approach is to allow Servicer and Client to interact, through their systems and functions, to better understand the capabilities of OOS applications. The interaction of Client and Servicer is proposed to identify emergent properties of this relation (for example operational constraints and systems design and operational requirements) and how such properties affect the design of both sides. Such properties can then be used for the readiness assessment of both Servicer main tasks/functions and Client systems and sub-systems, which enables the exploration of roadmaps for OOS, considering both sides. Additionally, this interaction feeds into the exploration of serviceable satellite designs for the Client side to be explored at early stages of a project.

The proposition is directly relevant to an area of OOS not explored in detail. Also relevant is the direct application of this solution in the current trend of changes towards OOS, with the recent increase in the interest in the commercial capabilities representing an important milestone. Thus, it is important to explore the integration of OOS to the current philosophy of systems design and operation. However, it is also necessary to capture the entire context of servicing, in which Client and Servicer operate under different views, interests and requirements as illustrated in Figure 4-1.

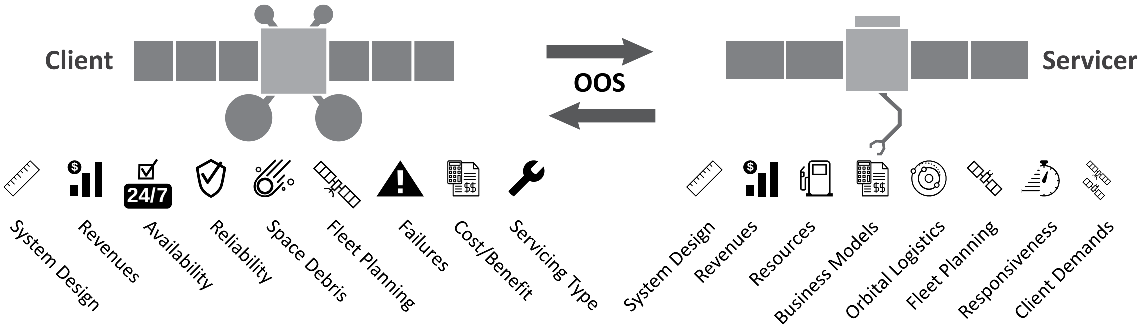

Figure 4-1 – OOS General Diagram - Context and relevant parameters for Client and Servicer

The figure captures the main points Client and Servicer are interested, no matter their specific application or operational concept. From these points a series of other specific metrics can be expanded as it will be demonstrated in the following chapters.

Considering that OOS has not been a dominant concept in satellite design and operation, it becomes challenging to introduce it as an option. Despite the current trends, satellite operators can still have cautious views of this area and be unsure about how OOS might fit into their current design and operation philosophies. Within this context, it is important to allow the stakeholders of this area to explore the potential challenges and benefits of this new approach.

Understanding the relation of Client and Servicer is a key point in the implementation of OOS. It is also a challenging task considering the number of parameters and perspectives to be considered. Thus, the implementation of OOS as part of space systems design and operation depends on the concurrent framework of the Client and Servicer relation. The framework to capture the Client and Servicer relationship is presented in the following section.

4.2.2 Framework

Based on the proposition of the Client and Servicer relationship, a framework using Agent Based Modelling and Simulation (ABMS) is established to address such concurrency in an OOS context. The framework (Figure 4-2) demands the consideration of stakeholders’ needs and requirements, an environment capable of simulating such relation, and a final representation of the effects of servicing for both sides for decision making. Further details of the decision to use ABMS are presented in Chapter 5.

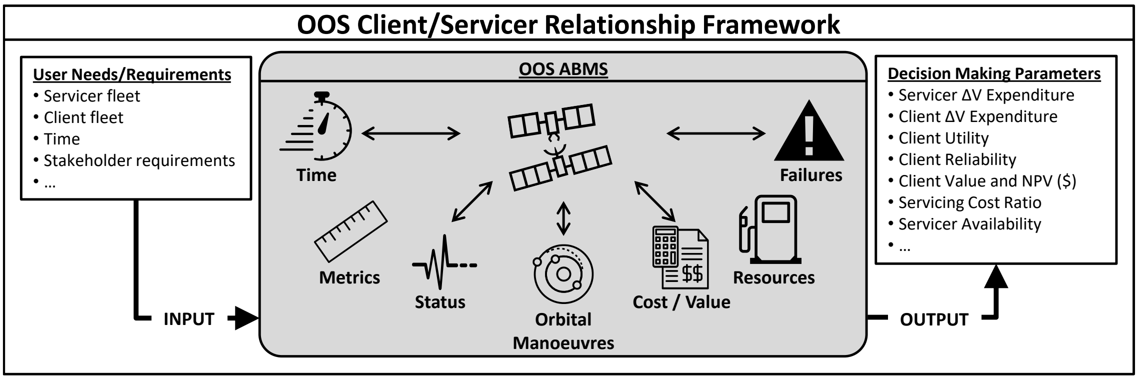

Figure 4-2 – OOS Client-Servicer Relationship Framework – Adapted from [144]

The framework proposed in this thesis and developed in the following chapters uses mathematical model simulation of the factors that are critical for the consideration of OOS. In addition to orbital manoeuvres, the space logistics, evaluation metrics and the knowledge of current OOS programmes provide the characterisation of the "agents" of the model (Servicer and Client) as well as their "states", "relations" and the "environment" where they are operating. In this way, different servicing applications and scenarios can be simulated and analysed in early phases of mission design of both Servicer and Client. The outputs can be used to:

- Analyse satellite servicing plans and operation scheduling to understand how the launch time and the expected servicing will affect the fleet operation;
- Analyse the system overall degradation to understand which type of servicing fits better for the satellites of a fleet;
- Simulate eventual failures and analyse the overall fleet response with and without servicing;
- Perform initial trade-offs and design of required systems to accommodate different types of servicing;
- Allow concurrent elaboration and refinement of Client requirements and Servicer capabilities;
- Analyse the cost-benefit of servicing compared to a "classical" fleet management approach.

4.3 Overall Methodology

Having defined the main necessary information about OOS, Client, Servicer and the implementation issues, the main methodology to enable the proposed solution is described as follows:

- A mathematical modelling of the framework is first presented and explored in detail. The mathematical modelling methods available in the literature are evaluated, to allow the most suitable method to be selected. This method is then used to model the main relevant points for Client and Servicer. Such points encompass how operators evaluate their systems, how servicing operations are supposed to happen and how the presence of Servicer or Client might affect their counterpart.
- Real satellite data is used in the framework to demonstrate how operators would use it in real life cases. Such demonstration also serves as an in-depth exploration and discussion of the different applications of servicing and their advantages and challenges from Client and Servicer views.
- Current relevant cases of OOS discussions and applications are simulated using the framework in order to show the current capabilities and the contribution of the results for the exploration of OOS.

The following chapters focus on the three mentioned items. Each chapter is mainly composed of content published separately in journal and conference papers focused on space engineering, systems engineering and concurrent engineering. The discussion and limitations of the methodology proposed are discussed in the final chapters summarising points observed in the other chapters.

5 OOS Framework – Mathematical Modelling

Modelling the Client-Servicer relation is the core part of the framework described in the previous chapter. In order to address the modelling of servicing, the following requirements need to be met.

- Both Client and Servicer perspectives towards OOS shall be included in the modelling and simulation process.
    - **Client perspective**: Client operator aiming for technical or financial benefits by using OOS solutions as an alternative to the conventional satellite operation approach (e.g. operation without servicing, launching new replacement satellites).
    - **Servicer perspective**: Servicer operator aiming to provide a commercial option of OOS with a specific business plan/intended profit at the end of life (EOL) of its system.
- In order to be relevant to the ongoing OOS scenario, the modelling shall include the main current commercial servicing options, i.e. main proposed applications. Additionally, the model shall allow the user, either Client or Servicer operator, to explore OOS options from their own point of view while concurrently considering the perspectives of their counterpart.
- Considering the emergent characteristics of OOS, the model shall also allow a consistent/unified (computational) environment to facilitate its use in early phases of the design and procurement for Client and Servicer.

5.1 Context

The relationship can be represented using different modelling techniques. From the perspective of systems simulation Discrete Event Simulation (DES [145]) and Agent Based Modelling and Simulation (ABMS [145,146]) are techniques commonly used. The first is suggested to model a system operating through a chain of specific events from its entities; the modelling of a queue (system) in a bank, for example. The second is used to represent a more complex system and the interaction of the agents composing such system [147]; the modelling of a traffic grid system in a city, for example.

Depending on the level of details and desired characteristics for the modelling, both methodologies would allow the characterisation of an OOS environment. Further considerations of each modelling methodology for systems simulation are discussed by Siebers et al. [145].

In the 1970's, the Comprehensive Operational Support Evaluation Model for Space (COSEMS) [148] was developed by the USAF to explore different components for a responsive launch and operation infrastructure. This Discrete Event Simulation was not directly intended for OOS and was used to simulate an infrastructure in space (the system) encompassing, among other features, basic representations for refuelling and replacement of satellites. However, specific details of the entities (satellites and launchers) and how they interact are left aside. More recently, Richards [149] presented a simplified ABMS to explore the orbital transfers for OOS, focused on cases of failure. The model brings useful insights on points related to availability of Client satellites for cases of failure. However, the model is still focused on cases in which servicing is used as a response to a failure only. In addition, it does not account for specific relationship parameters for Servicer and Client such as Servicer capabilities and limitations, Client compatibility, degradation and system characteristics. From a customer-centric perspective, Lamassoure and Saleh et al. [66,150] present a framework focused on Decision Tree Analysis (DTA) to understand the value of flexibility and cost-effectiveness of specific types of servicing, exploring in detail the uncertainty aspects faced by the Client regarding OOS. Yet, no specific relation of Client and Servicer is explored within that framework.

5.2 Related Research

In the context of the main problem stated previously and the solution proposed by this research, it is useful to highlight from the literature review some previous or ongoing research in similar or parallel areas. The main related research indicated is in the overlapping area of systems and concurrent engineering and On-Orbit Servicing.

The group headed by Rhodes and Hastings [151] and Miller [152] are active on the research using Systems Engineering techniques, applying this to a variety of areas, including the exploration of problems of space engineering.

Richards [153] presented the study of serviceability of satellites currently in orbit to specific OOS applications. Even though technical considerations for future architectures are discussed, the methodology is limited in assisting the satellite operator on the design of a serviceable satellite. Additionally, the main current issue of OOS at its design and implementation phases: the relation between both sides, are not approached. Richards' study regarding the use of Agent Based Modelling and Simulation (ABMS) for orbital transfers is presented separately in a different publication [149]. The Agent Based Model presented in that work uses Servicer as main agents and considers only orbital manoeuvres, specifically GEO orbital phasing. Specific characteristics of servicing applications such as functions and compatibility are not assigned to the agents of the model. Mainly focused on response to failures, the failure rate characterised in the model estimates more occurrences than the expected probability presented in that work [149]. Most important, the approach of servicing based solely on failures used in the model does not build a strong case to represent OOS capabilities; this is addressed later in this thesis.

Long discusses the economic feasibility of architectures for OOS [154]. The value analysis from Long focuses on communication satellites and the specific characteristics of them such as the number of transponders and the revenue per each one. Using an approach similar to "reservation price", Long identifies the maximum price the operator would pay for servicing and compares this with the minimum price achievable for a Servicer operation. As it will be discussed in the next chapter, the general "appreciation" of the satellite by its operator as a function of time might vary and should consider a group of factors/metrics. Constraining the analysis of OOS just to financial parameters can lead to a limited view of its advantages and challenges.

Both cases, although insightful in their main propositions and concepts, focus mainly on the Client side, with a limited leverage for iteration and discussion with the Servicer side. In addition, is important to distinguish this research from:

- Servicer design as generally explored in the literature.
- Business model proposition for OOS.
- Modular architectures for ground or space operations.

5.3 Methodology

This section presents the methodology for the implementation of the model proposed in this chapter. The main concept of the model, the mathematical background and specific exploration features are described in the following sections.

It is important to highlight that, considering the model requirements presented in the beginning of this chapter, the concept of operation and the implementation presented herein are focused on GEO satellites. This is discussed in the end of the chapter regarding the implications of using the framework for non-GEO scenarios. Later, in Chapter 8, more discussion is added regarding to non-GEO scenarios.

5.3.1 Modelling and Implementation

The main rationale behind the model is to allow the user, either Client or Servicer operator, to input their needs and requirements in a single model to simulate OOS scenarios. Among different modelling techniques some can be used for simulating OOS scenarios, such as Discrete Event Simulation (DES) [145], Stochastic Simulation or Agent Based Modelling and Simulation (ABMS) [145,147]. In summary, DES would be appropriate to a pre-defined (in time) sequence of events happening independently with Client or Servicer, assuming no changes in the system between such events. Stochastic Simulation would be applicable to simulate events of random nature assuming certain probabilities (e.g. failures). In ABMS different entities/agents interact with each other in a complex environment defined by specific rules of interaction and/or behaviour [147]. Such rules can be used to define how an agent changes over time and the outcomes of the interaction with another agent, not necessarily at a pre-defined time. Depending on the main objective of the modelling, either of the methods discussed could be used for OOS.

The objective here is to simulate the operation of Client and Servicer over time, including the changes in the system and conditions that might trigger specific events. Additionally, such events could depend on the presence of the other system (Client or Servicer). Agent Based Modelling and Simulation is used in this work in order to consider each agent (Client and Servicer satellites) as a single entity, and most important, because of the interaction of different agents of the system. The general operation of the model is described as follows:

1. The simulation runs for a given time defined by the user. At each time step the model calculates all the different parameters for each agent of the simulation (multiple Clients and Servicers).
2. The agents of the simulation are defined using the stakeholder inputs (systems characteristics, operational requirements and desired/expected services). Additional methods, well established in space systems engineering, are used to complement the agents' definition if the user does not provide enough data. The main methods here are to use cost estimating relationships (CERs) and historical data for satellites of that class and mass budget.
3. The state and condition of the agents are defined by the main metrics of each system. Propellant consumption, subsystems obsolescence/degradation, reliability degradation, operations cost, and time value of money are the main drivers of such metrics.
4. Failures can be included based either on a user-defined case or a random/stochastic way based on a given failure rate. For user-defined failures, the user provides the inputs defining a given capacity loss at a given time of the operation. Stochastic failures are generated based on a maximum number of failures per year, which is ten used to check the probability of a Client to fail at each time-step of the simulation.
5. Once one of the conditions to trigger service is met, a ticket is generated, and the Client is considered in a waiting list until a Servicer is assigned to it. The Servicer assignment depends on its compatibility with the requested type of servicing and on the availability at that moment, which includes availability of resources (e.g. propellant, payloads).
6. Once assigned, a Servicer will spend a portion of the servicing time in an orbital phasing manoeuvre [155,156] (Also described in Appendix D). The characteristics of such manoeuvre are dependent on Servicer and Client positions and the ticket priority. Failure cases are considered high priority while scheduled servicing cases are considered normal priority. Such characteristics

will dictate the time for the manoeuvre, the resources spent and the cost for the operation.

7. When a Servicer arrives at the Client orbital slot, it will start the rendezvous and proximity operation (RPO) prior the final docking/attaching. This phase of the operation is represented by a pre-defined time for RPO and ΔV (propulsive capacity).
8. After RPO the Servicer is considered in actual servicing operation. The duration of this phase of operation depends on the type of servicing. The Client-Servicer system created for the period of the servicing operation will have specific characteristics that might affect either Client or Servicer metrics.
9. After the servicing phase is completed the states and conditions of both Client and Servicer will change accordingly. The Servicer is considered to remain in the vicinity, however without interfering with the normal operations of the Client. The ticket assigned to that servicing operation is then considered as closed.
10. Once a ticket is closed, the final charges for the servicing operation are calculated. The Client satellite is charged by the Servicer at the time step the ticket is closed based on the resources spent in the entire operation (propellant and time).
11. If a Servicer has compatibility for "self-maintenance", it can move to a specific base for replenishment of resources. Although this is not completely adopted in the current scenario of servicing, the role of a replenishment base is discussed in the literature [157,158] regarding its benefits for an orbital infrastructure, therefore included in the model.
12. For the case of a Client that could not be serviced, the current state and condition will continue until the satellite ends its operational life. Depending on the condition that triggered the servicing request (e.g. failure), the operational life can be significantly reduced compared to the initial designed life.
13. When a Servicer reaches the end of its nominal design life or the end of resources, it will not be able to provide any service. For the first, the satellite will be considered dead, for the second the Servicer will remain unavailable (station keeping) until it reaches the end of its own propellant.

It should be noted that the presented concept of operation for the modelling is applicable to satellite operations and servicing in general. However, considering the requirements defined previously regarding the relevance of the model to the ongoing OOS scenario, the content presented in this work focuses on the operation and servicing of geostationary satellites.

Although commercial options dedicated to ABMS are available [159], the whole modelling is implemented in Excel VBA environment. This is due to the general accessibility and low computational power needed, in addition to the well-established use of this environment for systems and concurrent engineering [160]. The model is organised modularly, with a main module (Figure 5-2) guiding the simulation and calculation through a series of primary modules (Figure 5-3) in charge of specific calculations for agents' definition, states, conditions and metrics.

5.3.2 Applications, States, Conditions and Metrics

Based on the current trends towards commercial servicing, the main applications implemented at the current stage of the model are those derived from the OOS applications described previously.

- *Lifetime Extension – Full Station Keeping (LE-FULLSK)*: Servicer provides attitude control and station keeping throughout the entire extension time required.
- *Lifetime Extension – North-South Station Keeping (LE-NSSK)*: Servicer provides attitude control and North-South station keeping (major source of propellant consumption) for regular and shorter intervals of time until the total required life extension is achieved.
- *Maintenance and Repair – Refuel Single (MR-RS)*: Servicer refuels the Client satellite once with the total propellant to achieve the life extension required.
- *Maintenance and Repair – Refuel Multiple (MR-RM)*: Servicer refuels the Client multiple times to achieve the life extension required.
- *Maintenance and Repair – Refuel Complete (MR-RC)*: Client satellite is launched with a reallocated mass budget, trading less propellant mass with more

payload mass. This reallocation will affect how the Client operates and generates revenue through time. Servicer refuels the Client with enough propellant to complete its nominal capacity.

- *Maintenance and Repair – Payload Augmentation (MR-PA)*: Client satellite is launched with additional interfaces to allow the later installation of hosted/additional payload. Servicer installs the additional payload at a required time.
- *Rescue and Recover (RR)*: Servicer responds to a Client failure, limited to mechanisms deployment such as solar arrays and antennas.

As described, throughout the simulation agents will change their states and conditions based on the system behaviour, degradation with time or failure. Herein, a State is defined as a momentary characterisation of a system (Client and Servicer) based on its operational and servicing requirements; and a Condition is defined as the irreversible or permanent characterisation of the Client based on the change of its state. Such differentiation is necessary to identify the possible outcomes of a system through its life with or without servicing. The main states that a Client and a Servicer can have are:

- *Inactive*: Client and Servicer state before starting the operation
- *Operational*: Client operating normally
- *Scheduled*: Client operating after a servicing ticket has been generated
- *Available*: Servicer operating normally
- *Servicing-Phasing*: Servicer phasing to the Client orbital slot after being assigned to a ticket
- *Servicing*: Servicer performing the main servicing tasks on a Client satellite
- *Servicing-Base*: Servicer performing self-maintenance tasks at a fuel depot
- *Dead*: Client or Servicer out of operation due to the end of life or fatal failure

Additionally, in order to facilitate output handling, the different Client conditions are included:

- *Original*: Client satellite original condition
- *Failed*: Client satellite failed condition
- *Serviced*: Client satellite serviced condition

The changes of states and conditions described previously are illustrated in Figure 5-1 for Client and Servicer.

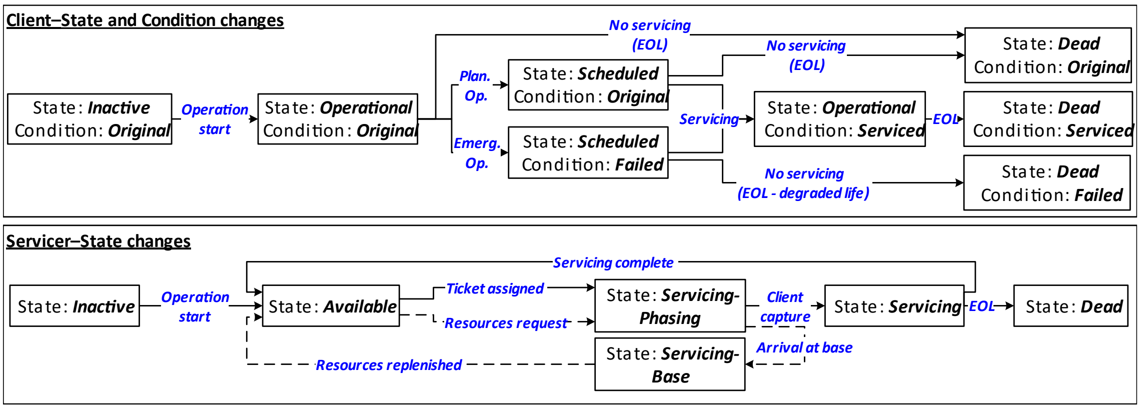

Figure 5-1 – Diagram of States and Conditions changes

Finally, to generate a complete set of outputs for the concurrent analysis of OOS from both Client and Servicer perspectives, technical and financial metrics need to be considered concurrently.

Technical Metrics: Metrics describing the operation and the degradation of the system and subsystem with time.

ΔV: Describes the propulsive capacity and how it changes with time depending on orbital manoeuvres, station keeping, propellant transfer, failures and servicing. It is calculated based on the designed life (t_{Life}), orbit insertion characteristics (Geostationary Transfer Orbit – GTO or Geostationary Earth Orbit – GEO) and propulsive system characteristics. For geostationary satellites, the total ΔV estimation considers the designed life (t_{Life}), ΔV for orbit insertion ($\Delta V_{insertion}$) and ΔV for station keeping (ΔV_{sk}). The estimation considers $\Delta V_{insertion}$ ranging from 1.5 km/s to 3 km/s [63,161], and ΔV_{sk} ranging from 0.04 to 0.06 km/s per year [63].

$$\Delta V_{Life} = t_{Life}\, \Delta V_{sk} \tag{5-1}$$

$$\Delta V_{total} = \Delta V_{insertion} + \Delta V_{Life} \tag{5-2}$$

The propulsive capacity reduces at each time step, here represented by ΔV_{step}, due to the station keeping and orbital manoeuvres. This is done in the model by simply subtracting the needed ΔV for a time step (ΔV_{step}) from the satellite's total ΔV at each time step i (ΔV_{ti}).

$$\Delta V_{step} = \Delta V_{sk}\, t_{step} \tag{5-3}$$

$$\Delta V_{ti} = \Delta V_{ti-1} - \Delta V_{step} \tag{5-4}$$

It is important to note that the use of low-thrust electric propulsion demands complex methods for estimation of ΔV necessary for orbit raising and station keeping. From the results presented by Dankanich and Woodcock [161], a ΔV ranging from 2.2 km/s to 2.9 km/s is estimated for electric orbit raising depending on the conditions considered. Losa [162] and Topputo and Bernelli-Zazzera [163] present different estimation methods using low-thrust for station keeping with results ranging from 69 m/s to 180 m/s per year. When using chemical propulsion, the rule of thumb for LEO-GEO orbit insertion and yearly station-keeping ΔV is around 1.5 km/s and 50 m/s per year respectively [63]. In both cases, the ratio between electric and chemical propulsion can be up to a factor of 2 [161–163]. This factor is considered in the framework only for electric orbit raising due to the conditions of this phase of the mission, involving parameters such as thruster acceleration, atmospheric drag, solar pressure and manoeuvre duration. For station-keeping it is assumed an estimation following the standard yearly ΔV requirements.

Nevertheless, the ΔV capacity of Client or Servicer can be defined directly by the user if necessary and such information is known for a specific case.

m_p: Describes the propellant mass and how it is consumed with time depending on orbital manoeuvres, station keeping, propellant transfer and servicing. It is calculated based on the satellite's ΔV, total mass (m_0) and propulsive sub-system characteristics (specific impulse – *ISP*). Using the basic rocket equation [63,155] m_p for orbit insertion ($m_{p\ insertion}$) and for life operation ($m_{p\ Life}$) are calculated as follow:

$$m_{p\ insertion} = m_0 \left[1 - e^{\frac{\Delta V_{insertion}}{g\ ISP}}\right] \tag{5-5}$$

$$m_{f\ insertion} = m_0 - m_{p\ insertion} \tag{5-6}$$

$$m_{p\ Life} = m_{f\ insertion} \left[1 - e^{\frac{\Delta V_{Life}}{g\ ISP}}\right] \tag{5-7}$$

$$m_p = m_{p\ Life} + m_{p\ insertion} \tag{5-8}$$

$$m_f = m_0 - m_p \tag{5-9}$$

From both $m_{p\ insertion}$ and $m_{p\ Life}$, the total propellant mass (m_p) and dry mass (m_f) can be estimated considering the total mass m_0 is known. The same ΔV_{step} for a time step described previously is used to calculate the consumption of propellant with time.

Utility: This metric describes the flow of service that a system is forecast to deliver over time (per unit of time), as presented by Saleh [164]. It is applied to the satellites of the Client fleet considering the individual design life (t_{life}) and obsolescence time (T_{obs}). *Utility*, as used herein, is considered as absolute for each Client satellite and does not change based on the presence/*Utility* of other Client satellites in the simulation. It degrades from the total initial utility (U_0) of the system (assumed as $U_0 = 1$ for a fully operational system at BOL) down to a residual value (0). It should be noted that the residual utility can also be made non-zero, according to the user's preference.

$$U(t) = U_0\, e^{-\left[\frac{t}{T_{obs}}\right]^2} \tag{5-10}$$

The use of *Utility* as presented herein is to capture the variation of usefulness of a satellite with time. Therefore, it is important to highlight the difference of obsolescence and degradation, characteristics related to the usefulness and operational time of a satellite. While the first can be linked to factors such as operational time, market changes or appearance of new operators/competitors, the degradation of a system is linked directly to the satellite design life (t_{Life}). Market changes and competition can be difficult to predict and to characterise in the current stage of the framework. Therefore, obsolescence and degradation are considered here as dependent only on the operational life of the satellite.

The characterisation of a satellite system by each individual sub-system would demand a complex modelling. However, a useful refinement of the system characterisation is possible by defining separately Bus, the basic infrastructure of the satellite system, and Payload, the infrastructure responsible for the actual mission and/or income generation, e.g. communication, observation. To represent the *Utility* of the system by the matter of Payload and Bus, two factors are applied to T_{obs} respectively. This is necessary to characterise properly the expected life of a satellite and the general trend of systems outliving their initial design life. The details for the calculation of these factors are provided in Appendix E.

$$T_{obs\,Bus} = 0.67\; t_{ref} \tag{5-11}$$

$$T_{obs\,Payload} = 1.50\; t_{Life} \tag{5-12}$$

When Client condition is Original: $t_{ref} = t_{Life}$

When Client condition is Serviced: $t_{ref} = t_{Life} + t_{extended}$

For the Client operator, the *Utility* of the whole system depends on the mutual performance or *Utility* of both Bus and Payload. In this way, for a matter of simplification, a heuristic approach is used with Payload and Bus to define the *Utility* of the whole satellite:

$$U(t) = \frac{U_0}{2}\left[e^{-\left[\frac{t}{T_{obs\,Bus}}\right]^2} + e^{-\left[\frac{t}{T_{obs\,Payload}}\right]^2}\right] \tag{5-13}$$

Although different approaches could be used to estimate the overall *Utility* of a satellite based on the relation of Bus and Payload operation, these approaches become specific to the type of operator or system.

The approach for *Utility* represented in the equation (5-13) considers an average value between Bus and Payload utilities, however, specific cases should be pointed regarding this approach. If the Payload has zero *Utility* while the Bus still presents a non-zero *Utility*, the total *Utility* of the system will be non-zero even though the satellite does not present any practical use for the operator from a Payload perspective. In this case theoretically, the *Utility* could be used to represent the potential of repurposing that satellite assuming its Bus would be useful to perform other tasks in an established servicing environment, e.g. store/transfer propellant, parts salvage. In practical terms, this would be unlikely to happen as a commercial operator would be driven by the *Utility* of the Payload. Additionally, the way the obsolescence time is defined for both Payload and Bus (Equation (5-11) and Equation (5-12)) constrains a condition where the *Utility* of the Payload reaches zero before the *Utility* of the Bus.

The opposite case, i.e. Payload with a non-zero *Utility* while the Bus has a zero value, can occur considering how obsolescence time is defined (Equation (5-11) and Equation (5-12)). The condition of a satellite operating its Payload after the depletion of the propellant is a practical representation of this case. In the simulation, the total *Utility* is considered to be zero from the moment a satellite reaches its operational life used as reference (t_{ref} = t_{Life} for Original condition and t_{ref} = t_{Life} + $t_{extended}$ for Serviced condition). In this way, the case of Payload with a non-zero *Utility* and zero Bus Utility does not occur in practical terms in the simulation.

Different approaches such as multiplying Payload and Bus utilities by specific factors could bypass the two conditions described previously. However, the exploration of this relation can be considerably extensive and closely related to a given operator activity (e.g. observation, communication). The approach as used herein, although simplified, is not critical and can be adjusted by the operator to better characterise the satellites before any further simulation and analysis, allowing personalised inputs for Payload and Bus obsolescence time.

As it will be discussed later, the capability of the framework to take personalised metrics from the user allows the consideration of other measures of *Utility* in parallel with the equations presented herein, based on the work of Saleh [165]. Considering the range of uses and applicability of the research presented by Saleh [165], the equations presented previously are used as the main way for calculation of *Utility* and system obsolescence. However, it is important to note that different operators will have different perspectives or profiles, changing how their systems and the obsolescence are considered. In order to consider such different views, the system obsolescence and *Utility* can be considered in the framework as a User Defined Function or even a simplified function such as a linear or other polynomial function.

Reliability: Describes the probability of the system to survive after a given time based on Weibull distribution [165]. This metric is commonly used in failure analysis [166] and is included in the model to characterise the period when Client and Servicer are in the attached/docked configuration. This specific phase of servicing is considered critical since the temporary system formed by the Client-Servicer configuration will have different characteristics from Client and Servicer individually, e.g. mechanical, dynamics, attitude control. Therefore, this metric is considered for Client and Servicer satellites with default values for Weibull scale (θ) and shape (β) coming from statistical analysis of satellites for a given date interval [165]. It degrades from the total reliability of the system (assumed as $R(t) = 1$ for a fully operational system at BOL) down to a residual reliability. By the end of life the residual reliability can range from 0.6 to 0.8 [165], depending on the Weibull parameters used. However, the residual value at the End of Life depends on the values used for Weibull scale (θ) and shape (β). These values can come from the statistical analysis of a given period, for example 2000-2017 as used in Appendix F. When in the Client-Servicer configuration, the framework considers for the *Reliability* the smallest value ($R(t)$) coming from the calculations using Client and Servicer parameters (θ and β). From other publications it observable that as earlier periods are analysed, different values for Weibull scale (θ) and shape (β) are identified which could lead to lower $R(t)$ by the End of Life. Another point to be noted regards to how the statistical analysis is performed, for example focusing on the failure of a subsystem which could lead to lower values for $R(t)$ as well. Some examples can be identified in other publications [166,167] when the analysis is focused on specific subsystems.

$$R(t) = e^{-\left[\frac{t}{\theta}\right]^{\beta}} \tag{5-14}$$

It is important to note that the use of *Reliability* as presented herein is not linked to the generation of failures. In addition to the two methods described in section 5.3.1 about the generation of failures, *Reliability* could also be used for this purpose. This would require the consideration of the different subsystems and their individual values for θ and β. However, the characterisation of the satellites' *Reliability* by all the subsystems is beyond the scope of this research. This characterisation and its inclusion in the framework in future works are discussed in Chapter 8.

Financial Metrics: Metrics describing the financial/monetary characteristics of the system and its operation, therefore, directly dependent on the technical metrics. Other characteristics such as stakeholder business model/plans also define the financial metrics.

Current Value: Describes the nominal value of a Client satellite and how it reduces with time considering a linear depreciation. It is calculated based on the satellite Cost as New (C_0), including the launch cost, and reduces from the initial Cost as New down to a residual value. Such approach is commonly used by commercial providers of satellite data [168] to estimate satellite values with time. The Cost as New is, by default, estimated using parametric models (QuickCost and USCM8 [63]) but it can also be provided directly by the user.

$$CV(t) = \frac{-Cost_{ref}}{t_{ref}} t + Cost_{ref} \tag{5-15}$$

When Client condition is Original: $Cost_{ref} = C_0$ and $t_{ref} = t_{Life}$
When Client condition is Serviced: $Cost_{ref} = CV_{t\,servicing}$ and $t_{ref} = t_{Life} + t_{extended}$

NPV: Describes the Net Present Value of a satellite based on the time value of money, operation costs and nominal revenues (from operation for the Clients and from servicing for the Servicers). Income capacity (Inc_{Cap}) is calculated based on the stakeholder parameters following the same methodology presented by Graham et.al. [28].

For the Client, Time to Break-Even (*TTBE*), discount rate (*r*) [5] and satellite cost as new (C_0) and are used to calculate the expected income at *TTBE* (Inc_{TTBE}) considering the time value of money, and its given capacity of income generation (Inc_{Cap}). Additionally, it is assumed that the income generation capacity (Inc_{Cap}) of Client satellites reduces with time, as a function of the *Utility* of the payload ($U_{Payload}$) and its obsolescence.

$$Inc_{TTBE} = \sum_{t=1}^{TTBE} \frac{1}{(1+r)^t} \tag{5-16}$$

$$Inc_{Cap} = \frac{C_0}{Inc_{TTBE}} \tag{5-17}$$

$$C_{Income} = Inc_{Cap}\, U_{Payload}(t) \tag{5-18}$$

For the Servicer the main income originates from servicing operations. Therefore, the income generation is calculated differently from the Client, depending on the charges

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[5] Time to Break-Even is used here as the time a satellite operator defines for a satellite to pay for itself from the revenues generated, and discount rate is the discount applied to the income with time used for a decision on the investment.

the operator applies to servicing (C_{Serv}). Considering that Servicer operators could aim for different business models, for a matter of simplification the Servicer perspective (described earlier) is the main guideline for the modelling. A given profit by the end of life (*profit*) is considered and the available resources (propellant – m_p) are used to estimate a charge per kg of it (C_{Serv}). Such charge is used to calculate the total cost of servicing (C_{Income}) considering the propellant spent in manoeuvres, tugging and refuelling ($m_{p\ Serv}$) while servicing.

$$C_{Serv} = \frac{C_0\ (1 + profit)}{m_p} \tag{5-19}$$

$$C_{Income} = C_{Serv}\ m_{p\ Serv} \tag{5-20}$$

For Client and Servicer, the cash flow (C_t) is calculated at each time-step considering a given operational cost (C_{OpCost} [6]) and then the *NPV* is calculated.

$$C_t = C_{Income} - C_{OpCost} \tag{5-21}$$

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + r)^t} - C_0 \tag{5-22}$$

Although *Current Value* and *NPV* metrics both deal with financial characteristics of the satellite, the main relation between them based on the way they are proposed in this work is at the beginning of life. Cost as New (C_0) is used as reference for the calculation of degradation in *Current Value* and for the calculation of return on investment in *NPV*. In the analysis, the two metrics could be used to explore the benefits of selling, operating and/or servicing a satellite. For example, *Current Value* would be used to give a selling value/price to that satellite if the operator desired to sell one of the assets. However, observing the *NPV* and how much return on investment was achieved, preferably beyond the brake-even point, would be also part of the decision. Those two values, at the instant of the decision, would be used to decide whether selling of keep

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[6] For timesteps when the Client is serviced, the cost of servicing is also considered as part of Client's C_{OpCost}. In this way, servicing costs are also discounted based on time value of money at the time of the ticket assignment.

operating a satellite would be the best decision. This relation becomes necessary in a well-established servicing environment where the potential of improving a system through its life is available.

Different operators/users will be interested in different metrics depending on their profiles and objectives. For example, *NPV* is commonly considered in commercial or financial evaluations (commercial operators) while *Utility* could be more relevant to a non-commercial operator. Therefore, the range of metrics presented before aims to cover such a range of potential users.

The variables related to the presented metrics are either provided by the user/stakeholder or assigned an assumed default value from the framework. This characteristic is discussed in the final section of this chapter. Additionally, other characteristics of the model are defined as follows and have a direct effect over the metrics and agents' states.

- <u>Compatibility</u>: Client satellites are defined with compatibility to a given application of On-Orbit Servicing presented in Chapter 2. For cases of refuelling, only Servicers with a compatible refuelling system (propellant type) can respond to a servicing call.
- <u>Self-maintenance</u>: Servicer satellites designed for *Refuel* applications are considered serviceable for the current cases. This allows these satellites to be refuelled once they are moved to a specific orbital location considered for a "fuel depot" infrastructure.
- <u>Charges</u>: The Clients are charged by the Servicers according to the type of servicing application. During the simulation the model does not decide on a best charge for either Client or Servicer. The point of view adopted when using the model will define this characteristic; this is discussed later in this chapter. Herein, the example assumes a Servicer operator aiming to pay for their systems by the end of the design life and a Client operator reaching better operational conditions when compared to the operation without any servicing. It should be noted that the definition of "better operational conditions" comes from the subjective view of each individual stakeholder.

In Table 5-1 are presented all the primary parameters the user needs to provide in order to simulate a desired case and the applicability to Client (*Cl.*) and Servicer (*Sv.*). These parameters are directly related to the metrics previously presented as well as to the type of simulation desired.

Table 5-1 – Simulation Primary Parameters – Description, remarks and applicability

Variable	Description	Remarks	Appl.
t_{sim}	Simulation time in years	-	-
n_c	Number of Clients	-	*Cl.*
n_s	Number of Servicers	-	*Sv.*
t_{Life}	Design life in years	-	*Cl.+Sv.*
t_{start}	Operation start time in years	-	*Cl.+Sv.*
T_{obs}	Obsolescence time in years	Based in t_{Life}	*Cl.*
m_0	Total mass in kg	-	*Cl.+Sv.*
$prop_{life}$	Propulsion type for operation	MP, BP or EP [a]	*Cl.+Sv.*
$prop_{insertion}$	Propulsion type for orbit insertion	MP, BP, EP or none [a]	*Cl.+Sv.*
β	Weibull shape parameter	Default = 0.387 [165]	*Cl.+Sv.*
θ	Weibull scale parameter in years	Default = 8338.491 [165]	*Cl.+Sv.*
Ω	Orbital slot (GEO) in degrees	-	*Cl.+Sv.*
i	Orbital inclination in degrees	-	*Cl.+Sv.*
a	Semi-major axis in km	-	*Cl.+Sv.*
Orb	Starting orbit	GEO or GTO	*Cl.+Sv.*
C_0	Cost as new in M$	Includes launch cost	*Cl.+Sv.*
C_{OpCost}	Cost of operations per year in M$ [b]	Default = 1% C_0 [63] [b]	*Cl.+Sv.*
C_{resid}	Residual cost in M$	Default = 5% C_0	*Cl.*
$TTBE$	Time to Break-Even in years	Default = 40% of t_{Life}	*Cl.*
r	Discount rate	Default = 6%	*Cl.*
$Serv_{type}$	Desired type of servicing	-	*Cl.*
$t_{extended}$	Desired extension time in years	For *Life. Ext.* and *Refuel*	*Cl.*
t_{serv}	Expected time to be serviced in years	As percentage of t_{Life}	*Cl.*
$fail_{rate}$	Failures per year	For *Rescue and Recover*	*Cl.*
$fail_{cap}$	Capacity loss due to failure in % of total capacity	User defined fail. case	*Cl.*
t_{fail}	Time of failure in years	User defined fail. case	*Cl.*
$m_{prop\text{-}sell}$	Mass of sellable propellant in kg	MP, BP or EP [a]	*Sv.*
$profit$ [c]	Servicer intended profit at EOL	As percentage of C_0	*Sv.*

[a] MP = Mono-propellant, BP = Bi-propellant, EP = Electric Propulsion

[b] Cost of operation assumed to cover all the ground operations and personnel. It should be noted that this value can vary drastically depending on the type of missions, e.g. communication, interplanetary, as well as the number of systems/satellites being operated. Therefore, the default value used is based on observed historic values for communication missions as presented by Wertz [63].

[c] Servicer *profit* is used as a simplified method to estimate the charges for servicing based on the Servicer cost and resources available. This is a necessary at this stage due to the lack of information about pricing/costs for the current proposed servicing systems. This allows the user to adjust this parameter based on the characteristics of their system and operation.

5.3.3 Solution Exploration

The modelling presented in the previous section brings together the important aspects of the Client and Servicer relation. However, even with the model implemented its use is still not trivial especially regarding the proper definition of the all parameters of the simulation. From Table 5-1 it is possible to summarise the information to consider Client and Servicer concurrently for different types of servicing. Having to manually/individually provide these parameters and explore the effect of varying them can be time consuming and difficult to estimate if the user needs to find a better solution.

Therefore, included in the model is a solution exploration functionality to facilitate the definition of user inputs. This functionality of the framework allows the exploration of the solution space for Client and Servicer. Also, the solution exploration highlights the concurrent characteristic of the model as it will be demonstrated later.

The solution exploration runs the framework consecutively, for a given set of variables. Those variables have their boundaries of maximum and minimum values defined by the user, as well as the step between maximum and minimum. The results for the consecutive simulations are grouped and presented in a colourmap chart where all the solutions can be analysed together.

However, the exploration of possible solutions and proper inputs can be applied only to specific cases of OOS in the model. Cases of failure response are not suitable for this type of exploration. Since servicing will restore the Client capacity to its nominal conditions, better results are achieved with the earliest response from the Servicer (Client minimum down-time). Cases of payload augmentation are dependent on the characteristics of the additional payloads being installed. Since the current information about the functioning or capacity of additional payloads aimed at OOS are still not publicly available it becomes difficult to estimate an optimum solution at this stage.

However, cases of extension of life (*Life Ext.* and *Refuel*) have characteristics to allow for the solution exploration. As both types of extension are dependent on the operation time of the satellites (either being refuelled or tugged), the simulation can be iterated for a range of inputs for Client and Servicer. Depending on the characteristics of the Client satellite, a better result can be achieved by performing the service earlier or later in the operational life. Similarly, the amount of extension in life depends on the satellite characteristics changing with its life so a better value can be identified. Since the outcome of servicing also depends on how the Servicer performs the operation, more specifically time and applied charges, parameters from the Servicer side must be considered.

In the model this is implemented by the iteration of four inputs presented in Table 5-2. The iteration follows the constraints the user (Servicer or Client) wishes to explore, with minimum and maximum limits as well as the intervals between.

The refinement of the exploration depends on the steps applied, in which smaller steps will generate a higher number of solutions and consequentially will take a longer simulation time. The parameters for the solution exploration for life extension are the following.

Table 5-2 – Solution Exploration – Iteration Parameters

Parameter	Description
Servicer Cost Ratio	Ratio (percentage) of the Servicer cost to an average Client cost
Servicer Profit	Servicer expected profit by the EOL as percentage of its cost
Client Life Extension	Client life extension as percentage of its design life
Servicing Trigger Point	Client time of requesting service as percentage of its design life

The average Client cost is also a necessary input although it is not iterated as the other four parameters presented in the previous table.

5.4 Model Implementation and Verification

The results of this chapter are separated two parts. The first part shows the implementation of the model discussed in the previous sections and its main characteristics. The second part is dedicated to the verification and demonstration of its main features.

5.4.1 Model

The model is arranged modularly, with a main module calling different other primary modules. Table 5-3 presents the name and description of the modules.

Table 5-3 – Main and primary modules

Module Name	Description/Function	ID
main_abms_module	Call primary modules	-
state_agent_start	Start the operation of each agent (Client or Servicer)	1
state_deltav_t	Calculate ΔV consumption at each time step	2
state_utility_t	Calculate *Utility* at each time step	2
state_reliability_t	Calculate *Reliability* at each time step	2
state_cv_t	Calculate *Current Value* at each time step	2
state_income_t	Calculate Income and *NPV* at each time step	2
state_fail_t	Verify for failure at each time step	2
state_array	Verify for state changes at each time step	2
state_servicing_start	Verify for the beginning of the servicing operation	6
state_servicing_complete	Verify for the completion of the servicing operation	2
state_tickets_close	Verify for tickets to be closed at each time step	3
aux_ticket_mnvre_calc	Calculate the phasing manoeuvre parameters (Client request)	5
aux_tickets_sort_order	Sort opened tickets by the order they were opened	4
aux_tickets_assign	Assign a Servicer to an opened ticket (requesting Client)	4
aux_mnvre_calc_base	Calculate the phasing manoeuvre parameters (base refuel)	2

The flowchart of the main module is presented in Figure 5-2. From the model description it is possible to identify the main processes related to the metrics calculation, change of states and servicing. Each of the processes in Figure 5-2 are identified by a number next to it so it can be cross-checked with the respective module in Table 5-3.

Indicated in blue in Figure 5-2 is the information exchanged between the processes. As described before, if the user does not provide non-mandatory inputs, the model uses parametric models and historic data to complete the definition of the agents.

The individual flowchart for each primary module is presented in Figure 5-3; the modules are indicated by the same name presented in Table 5-3. For the modules in Figure 5-3, the processes indicated with dashed lines represent the information stored for Servicer or Client at each time step.

The Solution Exploration feature uses the same flowcharts presented in Figure 5-2 and Figure 5-3. The four parameters described in Table 5-4 are iterated through the range defined by the user, being inserted in the input handling. The simulation runs with a given combination of parameters, the results are stored at the end and the next combination is iterated until all the solutions are explored for that range of parameters.

The current version of the model implemented in Excel/VBA environment focuses on the OOS applications discussed in this thesis. Experimental versions of different OOS applications are also included but are beyond the scope of the current work. The primary user interfaces for the model are presented in the Appendix G.

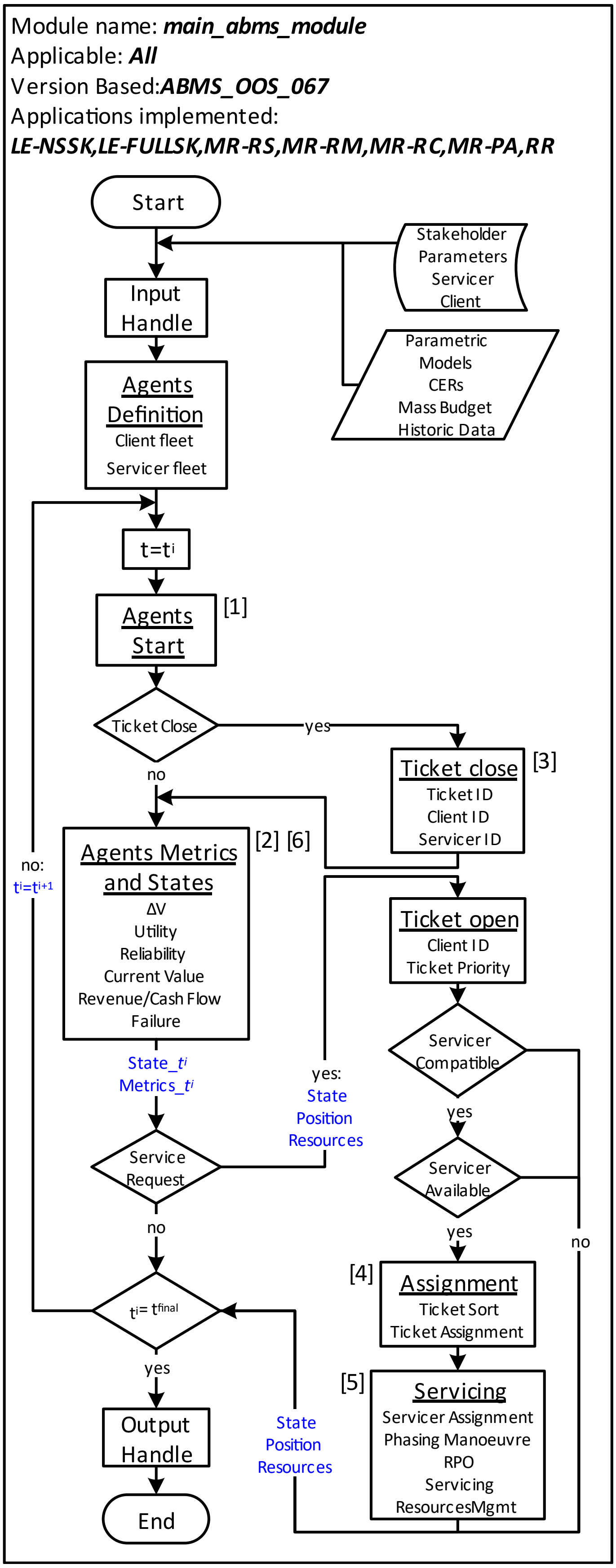


Figure 5-2 – Main module diagram

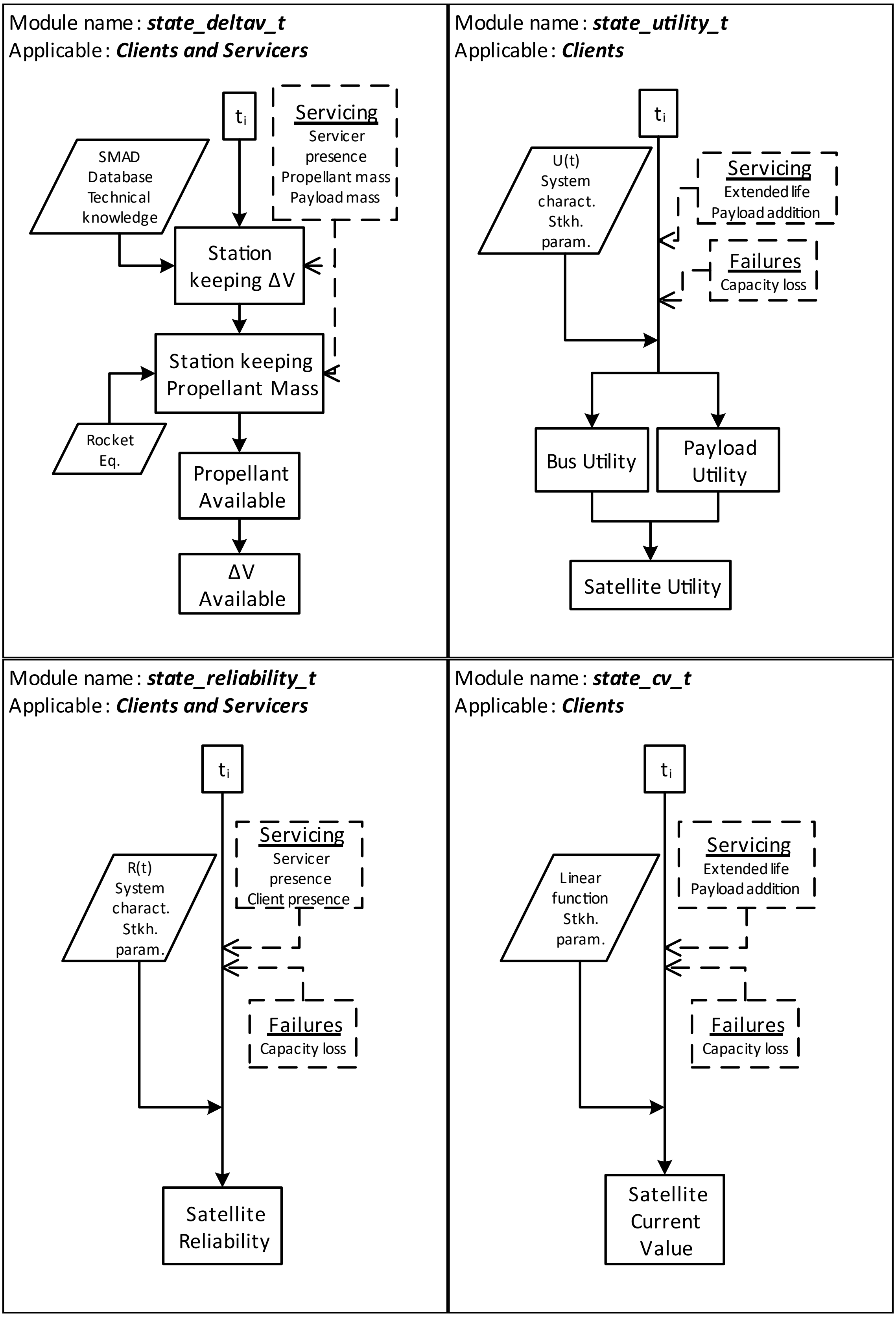


Figure 5-3 – Primary modules diagrams (Part 1 of 4)

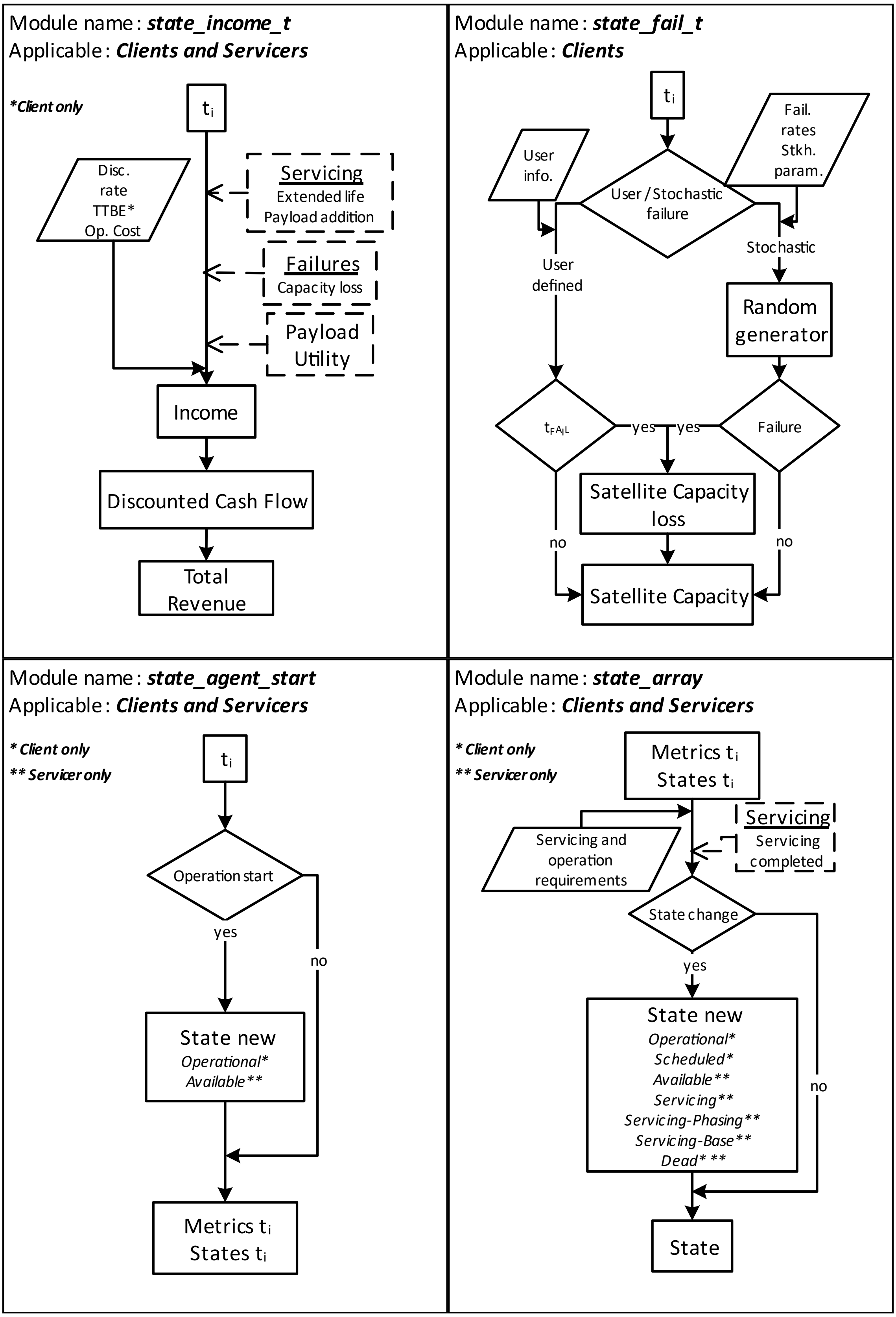


Figure 5-4 – Primary modules diagrams (Part 2 of 4)

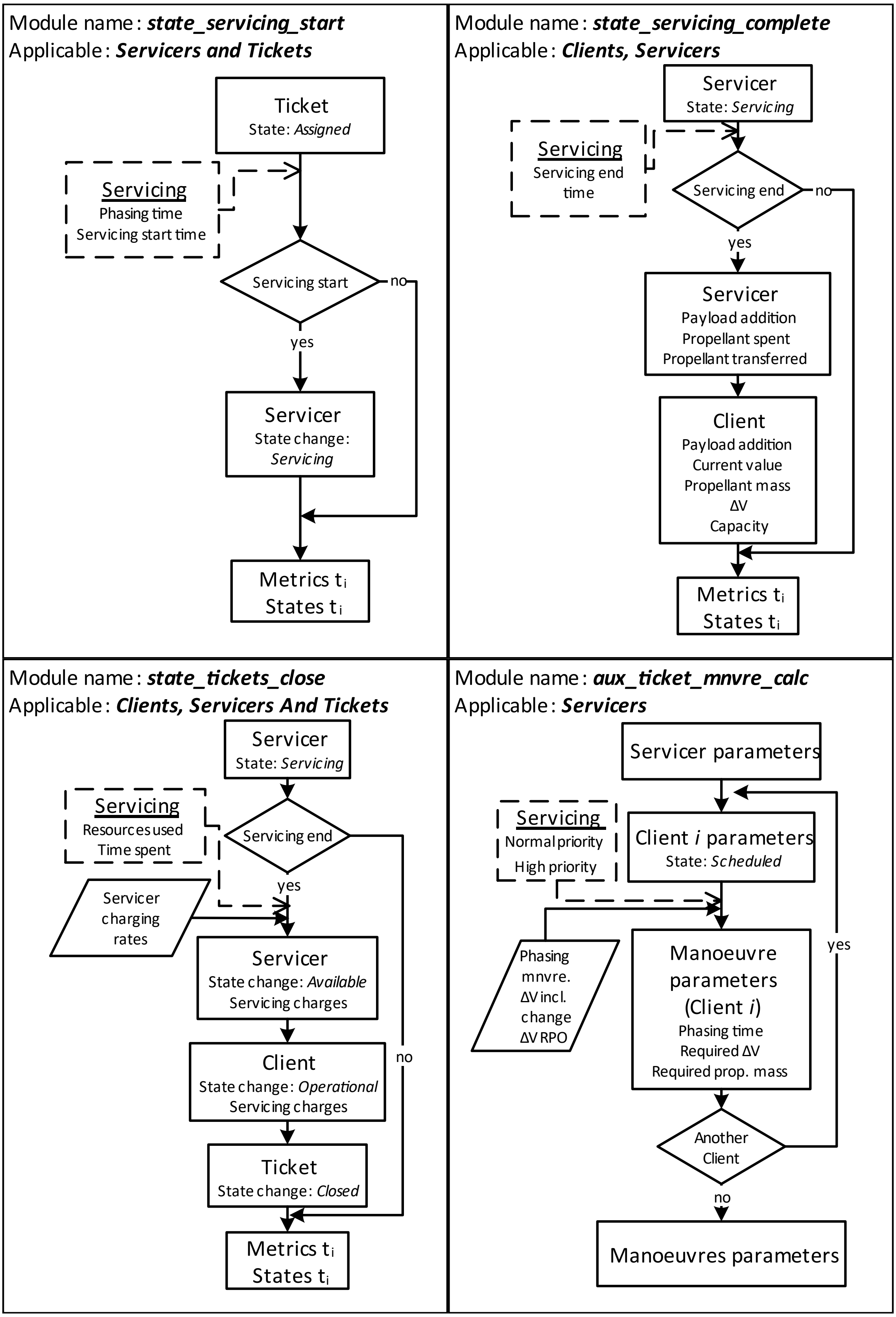


Figure 5-5 – Primary modules diagrams (Part 3 of 4)

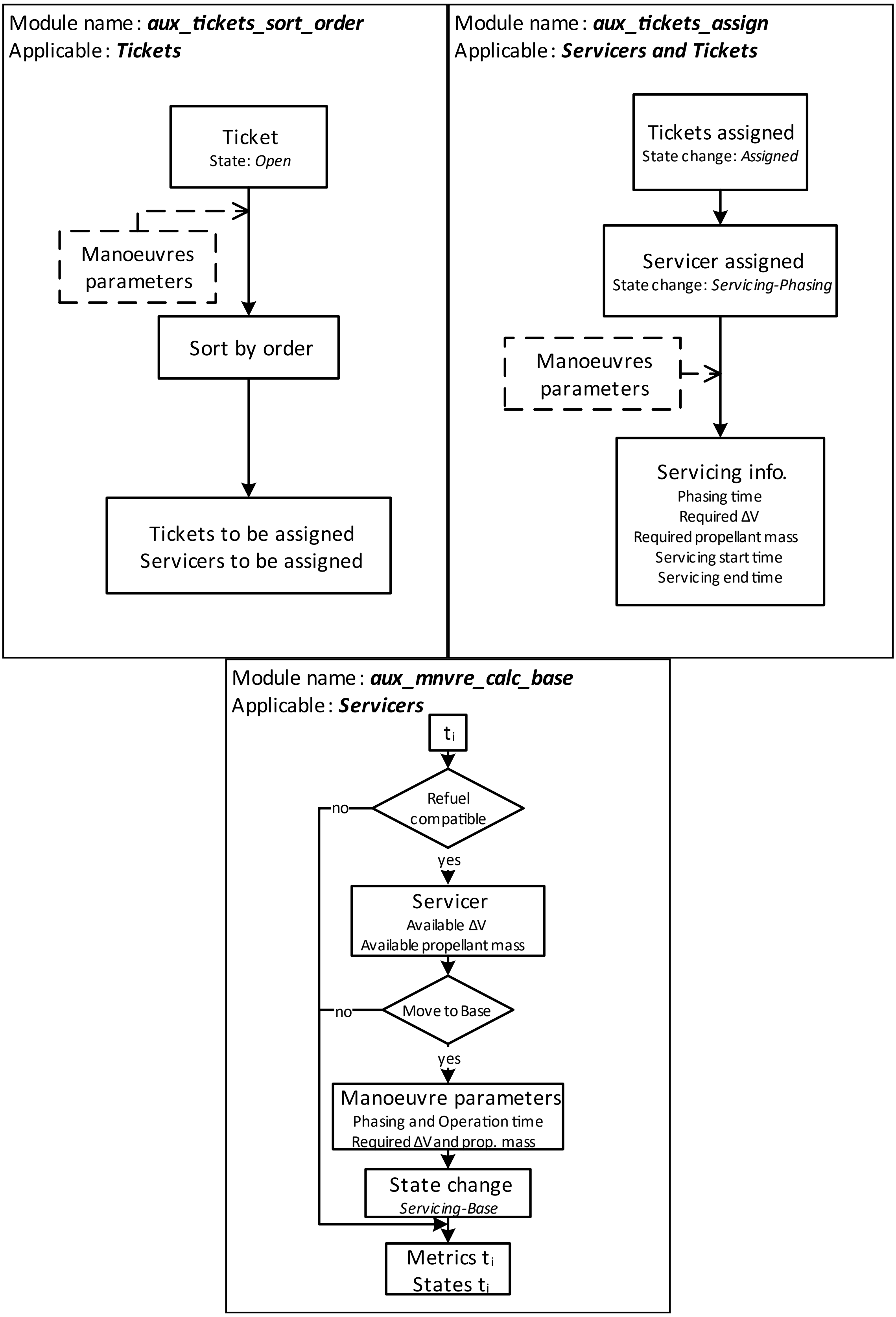


Figure 5-6 – Primary modules diagrams (Part 4 of 4)

In the Figure 5-7 is also presented a simplified diagram of how the information of the Main and Primary modules diagrams (Figure 5-2 and Figure 5-3 to Figure 5-6) and modules description and function (Table 5-3) can be used to track the information flowing in the framework.

The diagrams of Figure 5-2 work together with the information of Table 5-3 and Figure 5-3 to Figure 5-6. With these three sources the reader can understand the information considered and calculations/decisions made at each of the processes of the framework.

The simplified diagram presented in Figure 5-7 indicates how those three pieces of information work together for a step-by-step understanding of the framework and its processes.

Boxes indicated with dashed lines indicate the source of the information (from the content presented in the paper). Boxes indicated with full line (blue) indicate the information obtained from each of the sources.

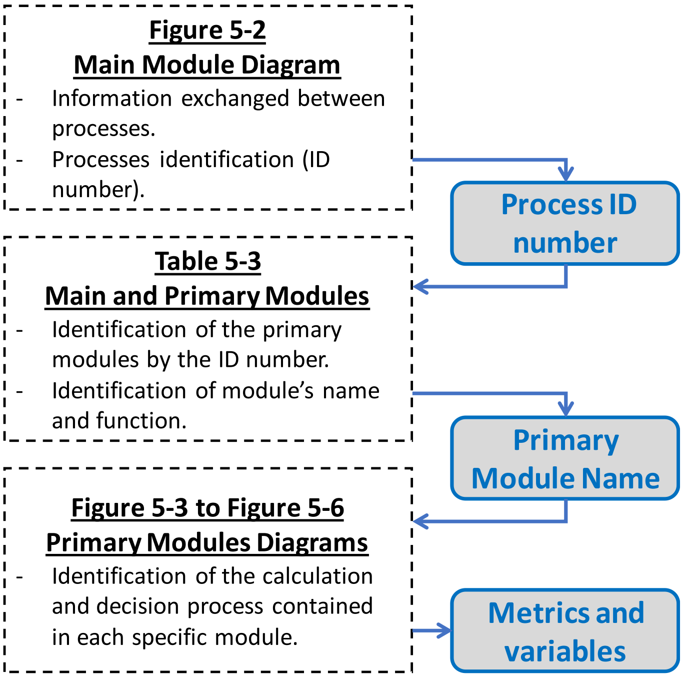


Figure 5-7 – Framework information sources – Process, modules, metrics and variable identification.

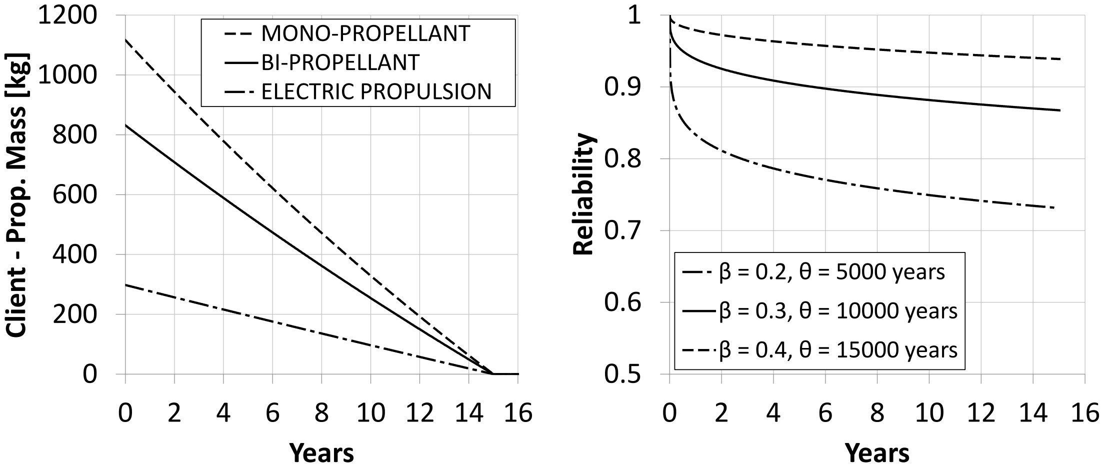
5.4.2 Verification and Demonstration

This section presents the verification and demonstration of the model presented previously against its main proposed capabilities discussed in the implementation section. It is important to note that, because OOS is a solution at early phases of implementation in the design and operation of space systems, the validation of such capabilities depends on further information still to be publicly provided. However, also as discussed in the implementation section, the framework allows the use of user specific parameters. In this case, the validation could be performed "in-house" based on the knowledge and expectations of each user.

For the verification of the model's main requirements (Figure 5-8 to Figure 5-11) and the demonstration of its capabilities (Figure 5-12 to Figure 5-14), simple cases are presented. To highlight the effects of different types of servicing, a baseline Client satellite with lifetime (t_{Life}) of 15 years is used as reference. Similarly, for the results related directly to the Servicer (Figure 5-11), a lifetime (t_{Life}) of 15 years is considered as reference. For the Client, the operation starts (t_{start}) in the first year of the simulation while the Servicer results show the operation starting prior to the first servicing request, around the year 9 for *Refuelling* and year 6 for *Lifetime Extension*.

Different values for the main input parameters are used to demonstrate the effect of them in the simulation of the satellites' behaviour and/or degradation. Considering that metrics such as ΔV, *Utility* and *Current Value* are mainly dependent on the system characteristics (satellite designed life, mass and cost), while they can be generated by the model, the demonstration of these metrics is skipped here. Despite m_p being also dependent on the same characteristics, different propulsion types can drive different user parameters and therefore the results are included in the verification. For *Reliability* and *NPV* different input parameters are demonstrated since these metrics include inputs specific to each user. This is used to highlight the capacity of the model in taking customised inputs from the user. The requirement of different perspectives for Client and Servicer are verified by the following pictures. The Client satellites represented in Figure 5-8, Figure 5-9 and Figure 5-10 start the operation at the first year of the simulation and finished the operation at year 15 of the simulation.

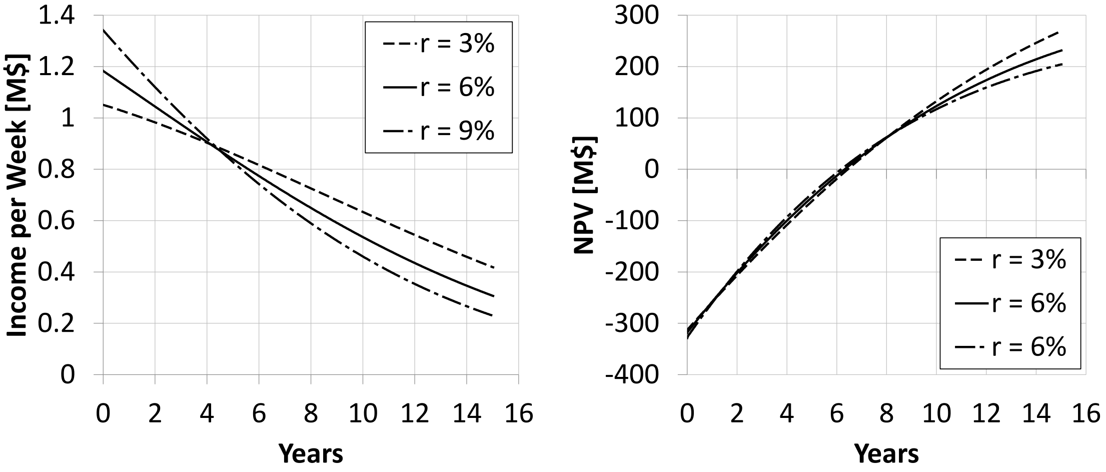
Figure 5-8 shows the m_p for different propulsion types and *Reliability* for different Weibull parameters (applicable to Client and Servicer). The decisions of the user regarding the propulsion types can affect the amount of propellant needed as shown in Figure 5-8a. This will drive then the satellite total mass and, consequentially, the total cost. Similarly, having a system with more or less reliability (e.g. existence or lack redundancies) can have direct effect on the operation and satellite cost.



(a) (b)

Figure 5-8 – Verification – Client m_p (a) and *Reliability* (b)

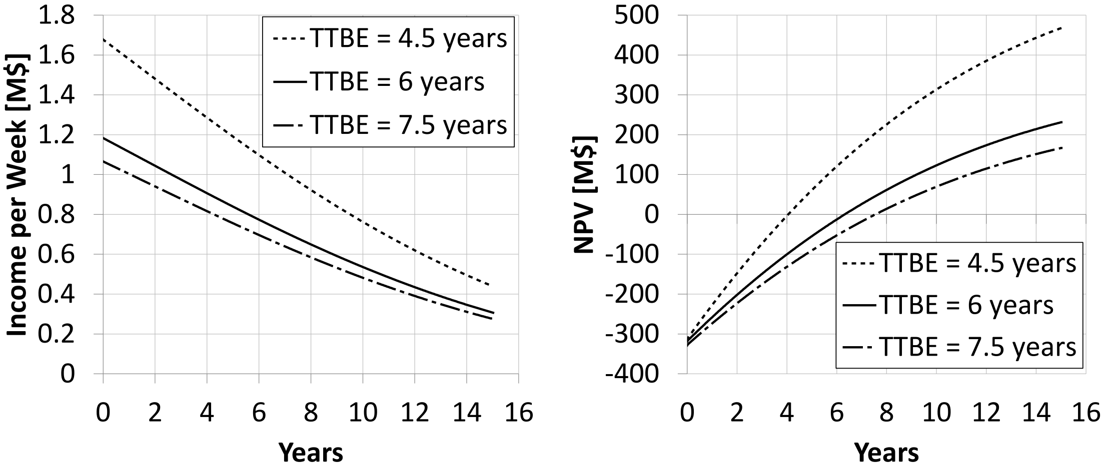
Figure 5-9 shows how different discount rates (*r*) affect the Client income generation capacity and the Client *NPV* (considering a default value of *Time to Break-Even* TTBE).



(a) (b)

Figure 5-9 – Verification –Income Capacity (a) and *NPV* (b) for different Discount Rates (*r*) – Default Time to Break-Even (TTBE = 40% of t_{Life})

Figure 5-10 illustrates the effect of different Time to Break-Even (*TTBE*) in the income capacity and *NPV* (considering a default value of *Discount Rate r*).



(a) (b)

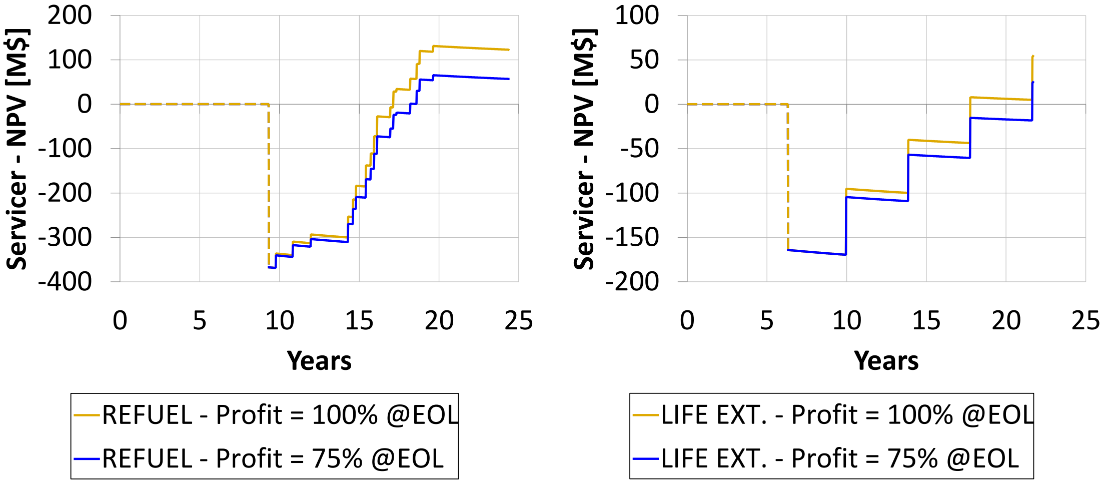
Figure 5-10 – Verification – Income Capacity (a) and *NPV* (b) for different Time to Brake-Even (TTBE) – Default Discount Rate (*r* = 6%).

Both metrics in Figure 5-9 and Figure 5-10 as well as the related input parameters can provide different user profiles (e.g. communications, Earth observation) regarding the operation/use of their systems.

The Servicer perspective is illustrated in Figure 5-11 showing the *NPV* for the system's life with different expected profits by the end of life. Likewise, different perspectives of operation or business models can be represented through this metric and the inputs defining it. Figure 5-11 shows results for *Refuelling* (*Maintenance and Repair*) and *Lifetime Extension* applications, however, the other applications described through the thesis have a similar behaviour with steps-up at each completed servicing operation.

Similarly, for the cases when a Servicer refuels itself at the refuelling base, the charges applied to the Servicer are represented by steps-down in the *NPV* curve. When a Servicer is not performing any servicing tasks, the costs with operation (ground control and personnel) will still be reduced from its *NPV*. This can be identified in the *NPV* by the decreasing slopes between the times a servicing operation is completed.

The Servicer in Figure 5-11a starts the operation (operational life) around the year 9 of the simulation while the Servicer in Figure 5-11b starts the operation around the year 6 of the simulation.

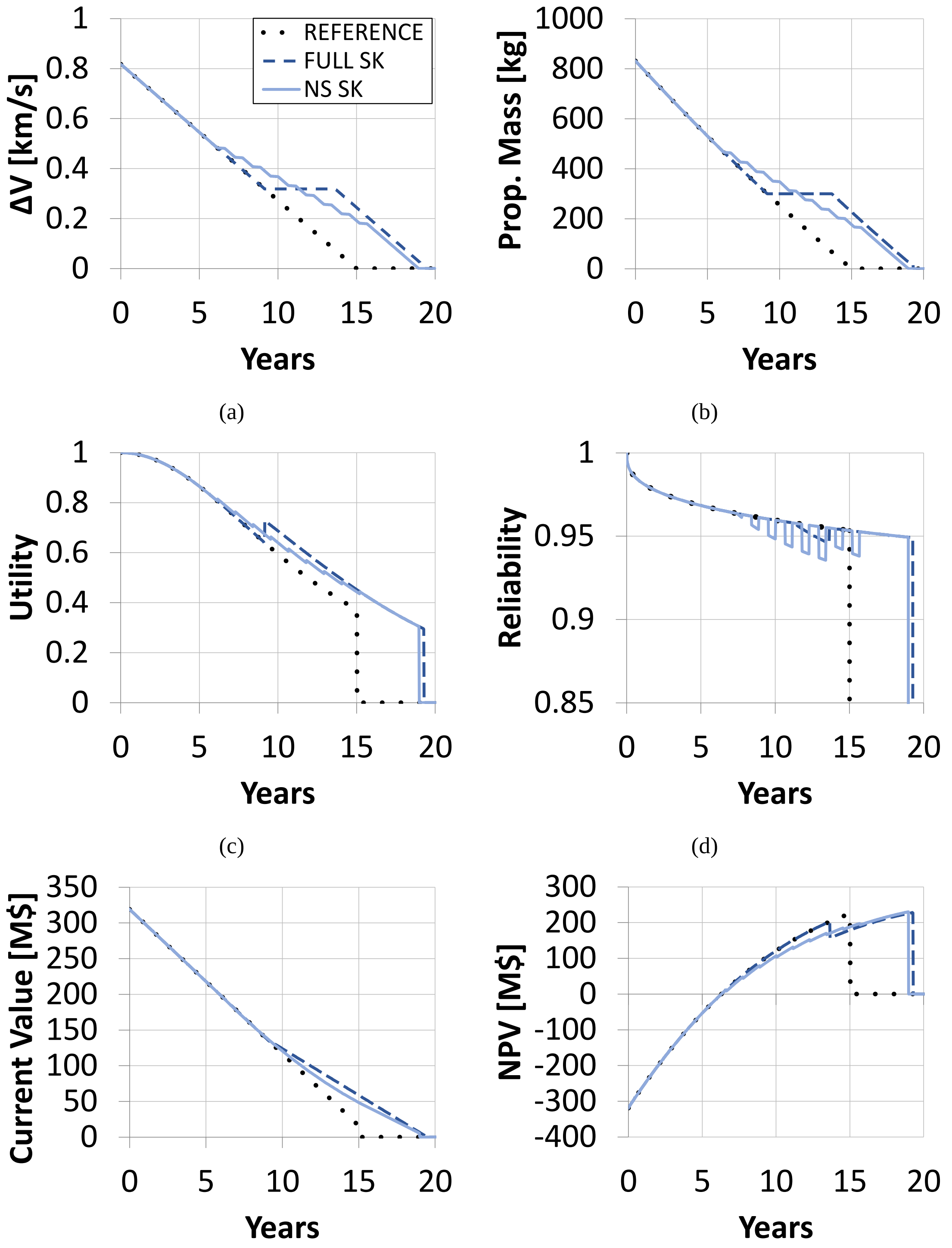


(a) (b)

Figure 5-11 – Verification – Servicer *NPV* for differet Servicer profit – (a) Refuelling and (b) Lifetime Extension

The technical and financial metrics defining the Client satellite are presented for the different types of servicing described earlier. A baseline Client satellite with t_{life} of 15 years is used as reference to illustrate the normal behaviour of the system without any type of servicing. The results for the metrics are the verification of the requirement of representing different types of servicing in the modelling and their effects over the Client operation. The in-depth discussion regarding the selection of one type of service over any other type is not discussed here as such a discussion would demand the proper definition of a contextualised use case. The definition and analysis of contextualised use cases using the framework are presented in Chapter 7.

Figure 5-12 presents the results for the two types of *Lifetime Extension*. The characteristics of the extension in one single servicing operation (*FULL SK*) compared to the extension with multiple operations (*NS SK*) is highlighted mainly by the ΔV and m_p (propellant mass). During the times of servicing, the Servicer oversees station keeping and orbital manoeuvres, which saves propellant of the Client (ΔV and m_p) and extends its operational life. This extension in life recovers *Utility* of the system and changes how the *Current Value* depreciates. Another important characteristic highlighted by the results is related to the *Reliability* during the servicing operation, when a third system (Client-Servicer) is created temporarily noted by the change of the curve shape/slope.



(a) (b)

(c) (d)

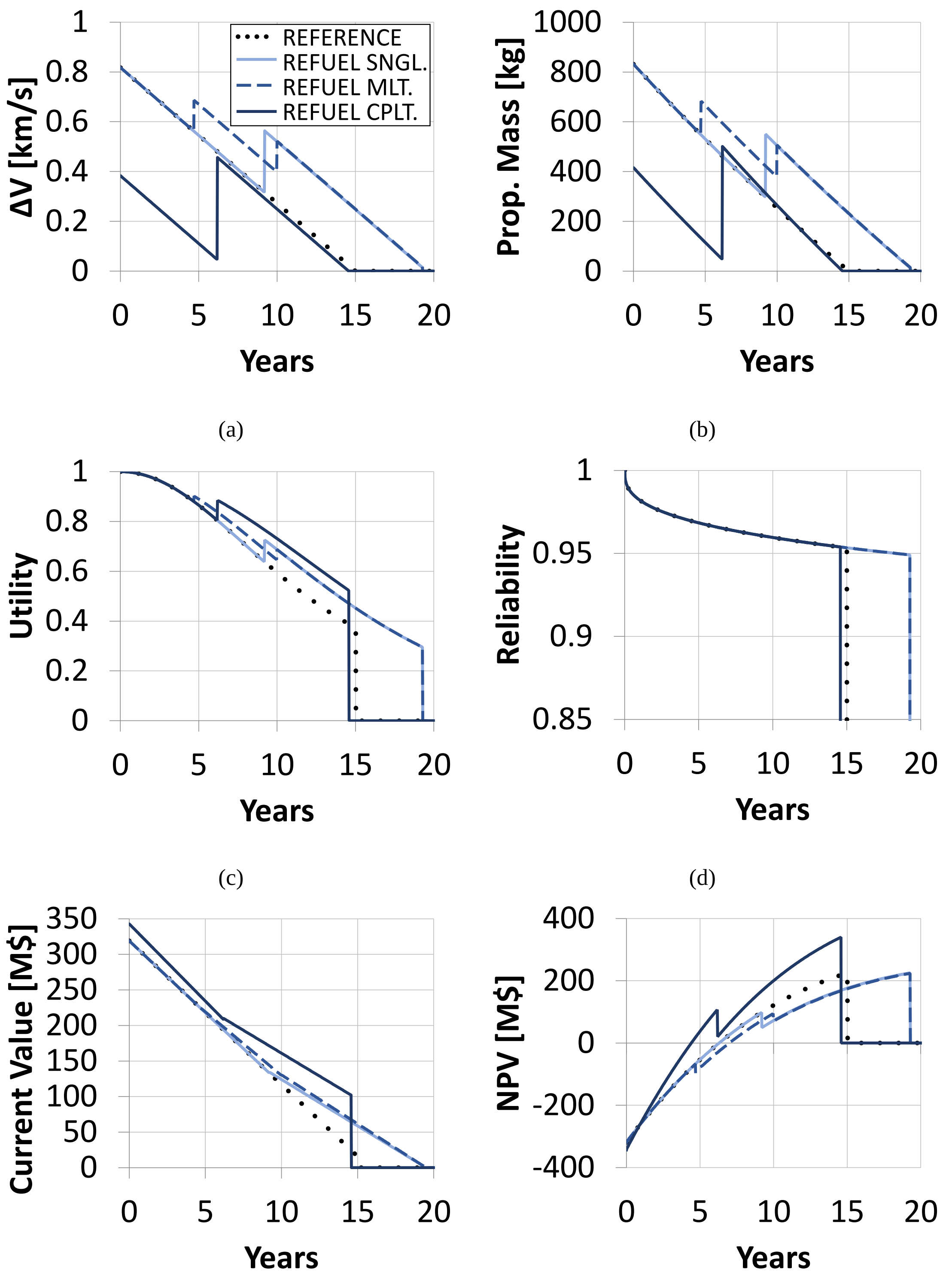
(e) (f)

Figure 5-12 – Demonstration – *Lifetime Extension* (*LE-NSSK* and *LE-FULLSK*)

It is important to highlight that the framework is independent of the operation of the individual modules, e.g. the user could change the parameters of the *Utility* function or *NPV*, so it could be refined by the user if they have better information. Another important point is that the *NPV* presented in Figure 5-12f and Figure 5-13f are not optimised, being just for demonstration and verification of the framework. Once more, the change of parameters for the metrics presented previously play an important role in exploring the benefit of servicing (discussed in Chapters 6 and 7).

For the case of *Refuelling* (Figure 5-13), the same metrics are presented, including a reference without any servicing. It becomes evident the difference of this type of servicing compared to the results for *Lifetime Extension*. Comparing ΔV and m_p it is possible to see when the Servicer refuels the Client in Figure 5-13 while the same metrics behave differently in Figure 5-12, in which the Servicer tugged the Client. For single and multiple refuelling, *Utility* and *Current Value* behave similarly to cases of *Lifetime Extension*. For *Reliability*, the effect in the Client satellite is less evident considering that refuel operations take considerably less time when compared to the extension cases in which the two systems are attached for longer periods. Additionally, for the case of *Refuel Complete* it is possible to observe how a Client with different mass allocation could have different characteristics. The exchange in propellant mass with payload mass is highlighted by m_p (less mass), *Current Value* (higher cost) and *NPV* (higher income capacity).

For both *Lifetime Extension* and *Maintenance and Repair* (*Refuel*), the Client is charged based on the expended resources and time for the entire operation, which can be seen in the *NPV*. Such value is added to the *NPV* of the Servicer as it was illustrated previously in the example of Figure 5-11.



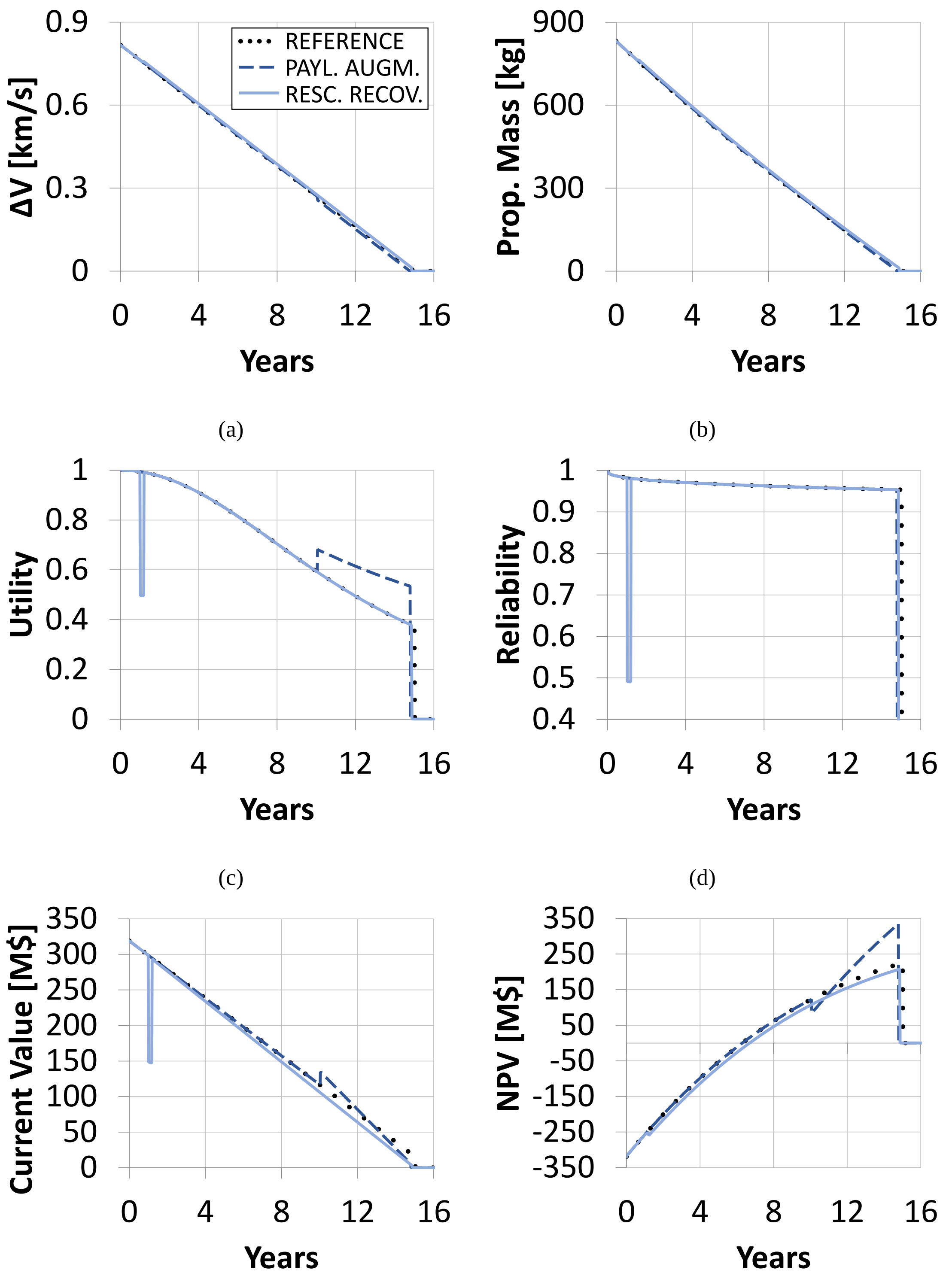
(a) (b)

(c) (d)

(e) (f)

Figure 5-13 – Demonstration – *Maintenance and Repair* (*MR-RS*, *MR-RM* and *MR-RC*)

Rescue and Recover and *Payload Augmentation* cases are illustrated in Figure 5-14. For the first, user defined parameters for failure (t_{fail} and $fail_{cap}$) were used for the demonstration. The failure happening around the first year of operation compromises 50% of the Client capacity. Until the Client is serviced, it operates in a degraded condition as it can be noted by the drop in *Utility*, *Reliability*, and *NPV* (the same effect is assumed to affect the *Current Value*). Once serviced, it is considered that the operation recovers the nominal Client capacity expected for that time of life. The case of *Payload Augmentation* assumes that the additional payload installed enables the Client satellite to change its income capacity (noticed by the change in the slope in *NPV*) and adds value to its *Current Value*. However, the installation of an additional sub-system changes the mass of the satellite, therefore spending more propellant for station keeping. This reflects in a reduction in the operational life due to the propellant.



(a) (b) (c) (d) (e) (f)

Figure 5-14 – Demonstration – *Maintenance and Repair* (*Payload Augmentation*) and *Rescue and Recover*

5.4.3 Solution Exploration

The results for the Solution Exploration are presented from Figure 5-15 to Figure 5-22. The exploration results are demonstrated for a fleet of 40 Client satellites (Figure 5-15 to Figure 5-18) and 80 Client satellites (Figure 5-19 to Figure 5-22).

The minimum and maximum boundaries for the exploration, as well as the step used are indicated in Table 5-4. The satellite average cost was considered fixed for the results presented herein, with the value of M$260. For the indicated parameters, a total of 5929 solutions were generated for each exploration (the product of individual n_{Sol}: in Table 5).

Table 5-4 – Solution Exploration – Iteration Parameters Boundaries

Parameter	Min.	Max.	Step	n_{Sol}
Servicer Cost Ratio	50%	150%	10%	11
Servicer Profit	25%	125%	10%	11
Client Life Extension	20%	50%	5%	7
Servicing Trigger Point	50%	80%	5%	7

For Client satellites, the result shows the average profit of the serviced life compared to the normal life without servicing. The Client profit indicated in the charts represents the additional profit above that achieved over a life without servicing. The results are presented in percentage of the Client satellite total cost (C_0)

The results for Servicer satellites show the average profit at the end of life. The profit is aimed by the Servicer operator and the results are presented as percentage of the Servicer total cost (C_0).

All the four parameters are iterated for the indicated intervals in Table 5-4, however, each individual chart represents directly the variation of only two of them, *Client Life Extension* (horizontal axis) and *Servicing Trigger Point* (vertical axis).

The variation of the other two (*Servicer Cost Ratio* and *Servicer Profit*) is demonstrated between figures as follows:

- The variation of *Servicer Profit* is presented:
    - Respectively between Figure 5-15 and Figure 5-16, and Figure 5-17 and Figure 5-18 for the population of 40 Client satellites.
    - Respectively between Figure 5-19 and Figure 5-20, and Figure 5-21 and Figure 5-22 for the population of 80 Client satellites.
- The variation of *Servicer Cost Ratio* is presented:
    - Respectively between Figure 5-15 and Figure 5-17, and Figure 5-16 Figure 5-18 for the population of 40 Client satellites.
    - Respectively between Figure 5-19 and Figure 5-21, and Figure 5-20 and Figure 5-22 for the population of 80 Client satellites.

The example presented here focuses on the financial metrics of the Client-Servicer relation, however the Solution Exploration generates the same range of results for each of the metrics discussed in section 5.3.2 of this chapter.

Maintenance and Repair (*Refuel Single MR-RS*) was the application selected to demonstrate the results. The choice for this application was to illustrate a large number of completed servicing operations. As it will be discussed in detail later in this chapter, refuelling cases have more flexibility to service multiple Clients, not needing to stay attached to the Client for longer periods as for *Lifetime Extension* cases.

The characteristics of the Client fleet can influence the result of the exploration as demonstrated in the fleet of 40 Clients (Figure 5-15 to Figure 5-18) and in the fleet of 80 Clients (Figure 5-19 to Figure 5-22). The areas of maximum average profit tend to stay around the same conditions for extension when comparing *Servicer Profit* and *Servicer Cost Ratio* in both fleets. However, specifically for the Servicer, the distribution of potentially attractive solutions becomes more concentrated for the results of a fleet with 80 Clients.

For the Servicer, the variation of *Servicer Profit* influences the average profit achieved but does not affect drastically the distribution of the solution for the servicing offered to the Client. They all tend to stay around the lower right corner, extending from 40% up to 50% of the Client’s life, with servicing happening from 50% up to 70% of Client’s operational life. The difference between the maximum average profit achieved by the Servicer and the initially intended profit (*profit*) is mainly related to the discount over costs.

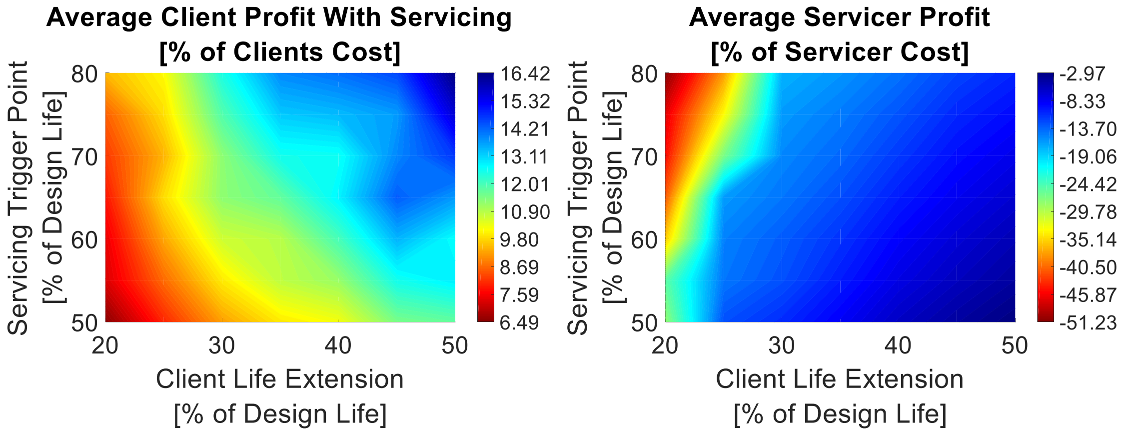
For the Client fleet, however, the variation of *Servicer Profit* changes the distribution of attractive solutions. As the Servicer aims for more profit, the amount of life extended tends to reduce for the Client. A Client life extension majorly ranging from 40% to 50% of Client life shows a common area of higher average profit (at the right side of Figure 5-15, Figure 5-17, Figure 5-19 and Figure 5-21), when a Servicer aims for a 25% of profit. When this profit is raised to 125% (Figure 5-16, Figure 5-18, Figure 5-20 and Figure 5-22), this region of maximum travels to the left side of the charts, with solutions ranging from 20% to 50% of Client life. This characteristic is more observable when comparing Figure 5-15 to Figure 5-16, and Figure 5-19 to Figure 5-20.

The Servicing Trigger Point is also affected by both Servicer cost and profit. As the Servicer becomes more expensive and/or the Servicer intended profit raises, the servicing trigger point tends to move later in the Client operational life. In the charts this can be illustrated comparing Figure 5-17 to Figure 5-18, and Figure 5-19 to Figure 5-20.

Another observed characteristic is how multiple areas of maximum appear in the solution with the Servicer aims for a profit of 25%. This is illustrated in Figure 5-15a, Figure 5-17a, Figure 5-19a and Figure 5-21a.

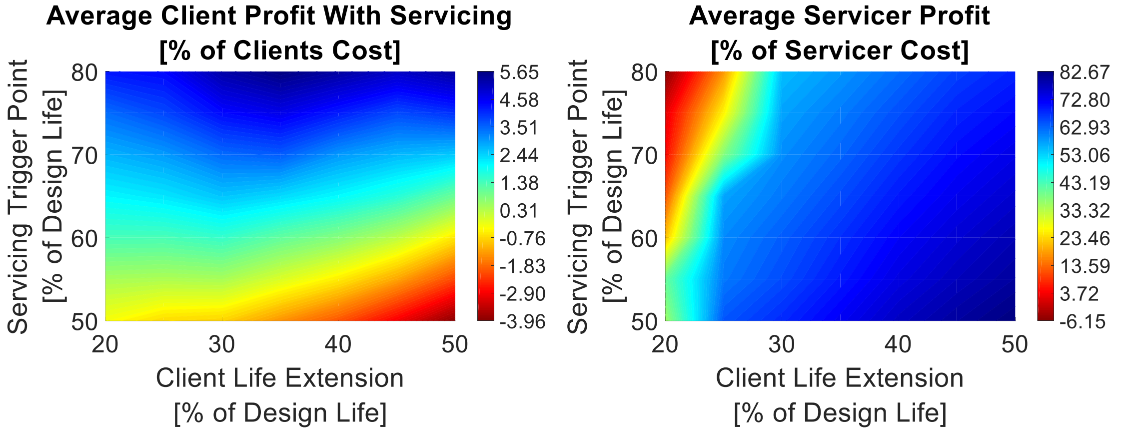
For the cases presented here, the average Client profit shows its dependence on the Servicer cost and expected profit, as would be expected. From the Servicer side, for an intended profit of 25%, the average profit achieved were all negative, not reaching the break-even point. It is important to note that the value presented in the chars is the average Servicer profit. Additionally, the discount over the servicing cost shows the influence in getting a profitable option for servicing. On the other hand, cases where the Servicer aimed for a higher profit resulted in an attractive option for the Servicer, with achieved profits all higher than 50% of the Servicer cost as new.

From the solutions explored herein, with boundaries defined in Table 5-4, the choice of demonstrating the two extreme values for Servicer profit was to highlight the effect of this parameters over the Client side. Although not presented in the previous charts, an intended Servicer profit above 35% already results in a profitable option for the Servicer side.



(a) (b)

Figure 5-15 – Solution Exploration – Client (a) and Servicer (b) Profits [7] – 40 Client satellites, Servicer C_0=390 M$, Servicer *profit* = 25%)



(a) (b)

Figure 5-16 – Solution Exploration – Client (a) and Servicer (b) Profits [7] – 40 Client satellites, Servicer C_0=390 M$, Servicer *profit* = 125%)

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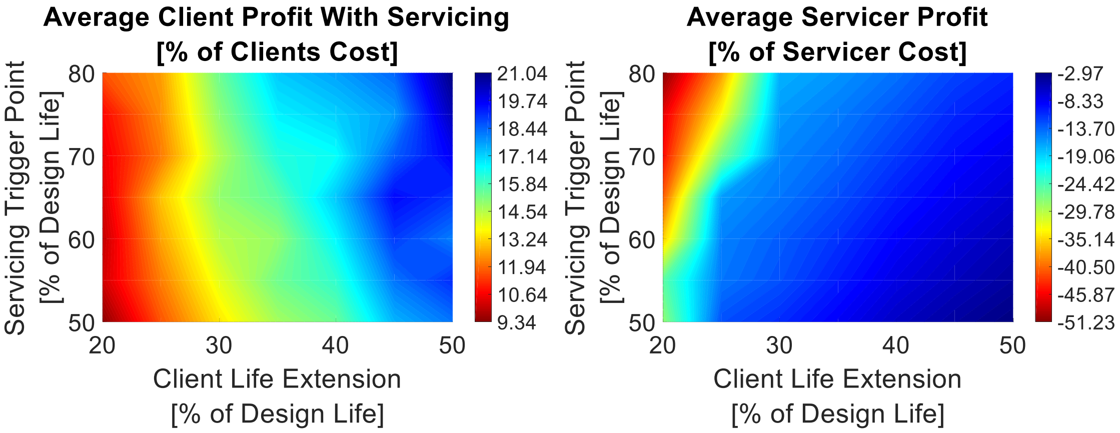
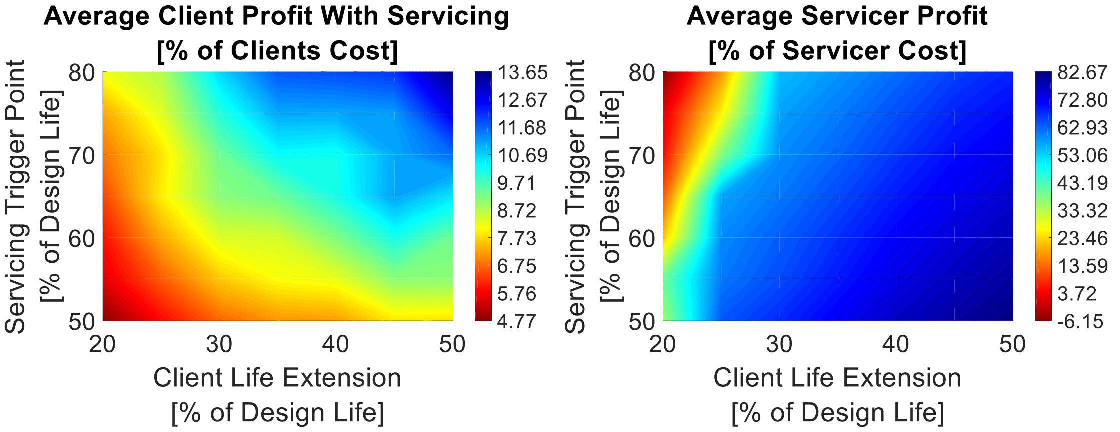
[7] For Clients it represents the additional profit above that achieved over a life without servicing.



(a) (b)

Figure 5-17 – Solution Exploration – Client (a) and Servicer (b) Profits [8] – 40 Client satellites, Servicer C_0=260 M\$, Servicer *profit* = 25%)



(a) (b)

Figure 5-18 – Solution Exploration – Client (a) and Servicer (b) Profits [8] – 40 Client satellites, Servicer C_0=260 M\$, Servicer *profit* = 125%)

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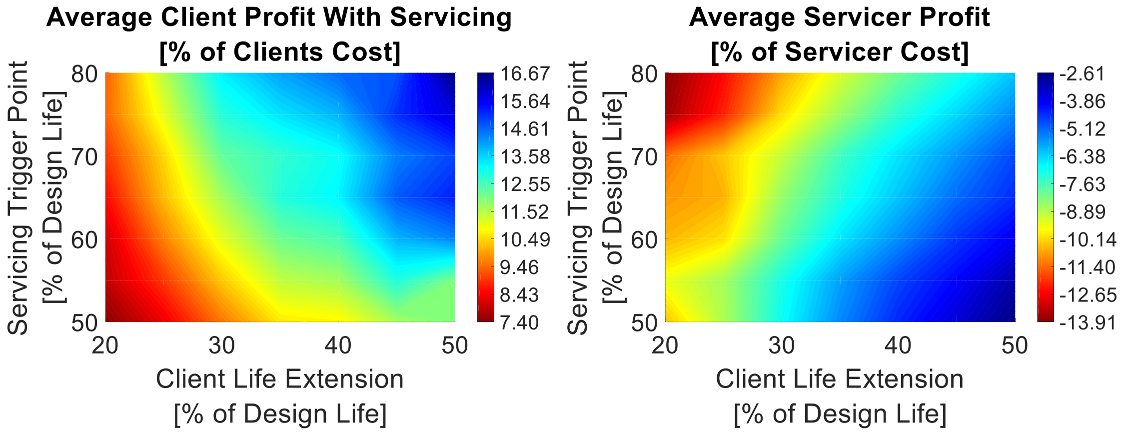
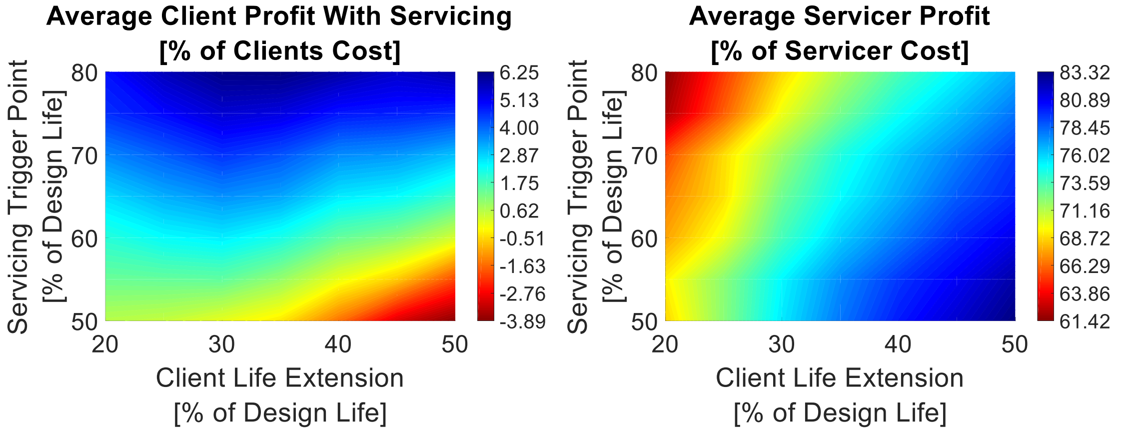
[8] For Clients it represents the additional profit above that achieved over a life without servicing.



(a) (b)

Figure 5-19 – Solution Exploration – Client (a) and Servicer (b) Profits [9] – 80 Client satellites, Servicer C_0=390 M$, Servicer *profit* = 25%)



(a) (b)

Figure 5-20 – Solution Exploration – Client (a) and Servicer (b) Profits [9] – 80 Client satellites, Servicer C_0=390 M$, Servicer *profit* = 125%)

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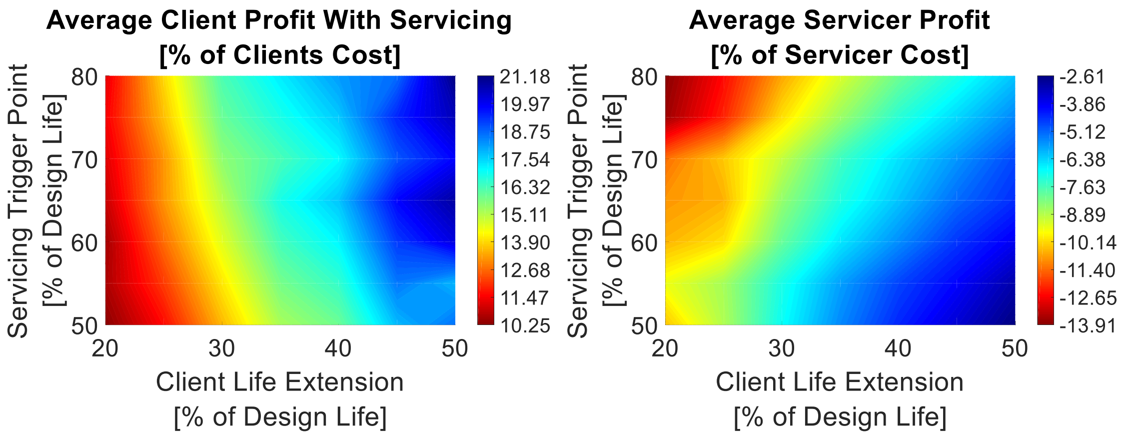
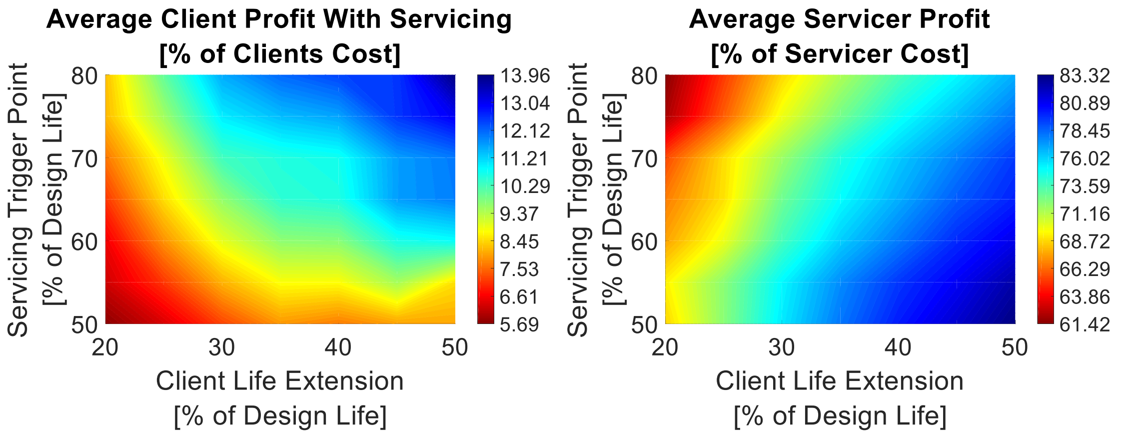
[9] For Clients it represents the additional profit above that achieved over a life without servicing.



(a) (b)

Figure 5-21 – Solution Exploration – Client (a) and Servicer (b) Profits [10] – 80 Client satellites, Servicer C_0=260 M$, Servicer *profit* = 25%)



(a) (b)

Figure 5-22 – Solution Exploration – Client (a) and Servicer (b) Profits [10] – 80 Client satellites, Servicer C_0=260 M$, Servicer *profit* = 125%)

The results presented herein for the Solution Exploration feature intend to highlight the characteristics of the framework as discussed in this chapter. Later, in Chapter 7, the Solution Exploration feature is used in a contextualised use case, based on a detailed definition of Client and Servicer fleet.

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[10] For Clients it represents the additional profit above that achieved over a life without servicing.

This section has presented the implementation of the model and provided some example results to verify and demonstrate its capabilities. The next section will discuss its features, applications and limitations.

5.5 Discussion

From the results presented in the previous section it is possible to verify the requirements proposed in the beginning of this chapter for the modelling of OOS.

The model was implemented in a well-stablished environment which enables its use independently of additional packages or dedicated software. The different features were arranged modularly to allow the replacement or addition of new modules. One point that was discussed through the chapter regards to the capture of the stakeholder perspective. Technical and Financial metrics are proposed to fulfil this requirement, however specific stakeholders might have specific ways of evaluating their systems, therefore needing extra characterisation of it. For this case, user defined functions (UDF) can be implemented in the model to allow the user to include their particular view of the system. Such functions can originate from personal expertise, heritage or can be specific to the type of the mission the system is designed for. For this reason, it becomes more difficult to include in the model as a standard feature. The verification of such functions can be subjective to each user and its demonstration to fulfil the model and user requirements would extend the work beyond its current scope.

However, considering the modularity of the model, the inclusion of UDF can be enabled in a simplified form, allowing the stakeholder to include polynomial or exponential functions, varying with the operational time of the system (designed life). The inclusion of UDF would demand its analysis in parallel with the other standard metrics (SM). Additionally, the effects of UDF over any of the standard metrics (SM) can be difficult to represent considering the possible combinations of UDF and a SM. Therefore, the analysis of UDF would need to be done in parallel with the SM already in the model.

Both Client and Servicer perspectives are characterised in the model and are dependent on the user input for the desired/intended system. The different systems' metrics help to characterise the user, independently on its segment (e. g. Earth observation, weather, and communications). However, as expected, more emphasis is given to the financial characterisation considering that the current endeavours in commercial servicing will be looking closely to this aspect.

Furthermore, the metrics help to consider Client and Servicer concurrently, especially regarding the influence of one system over the other/others. The presence of the Servicer to respond to a Client call, several Clients competing for a Servicer resource, or even two Servicers with different business proposals are examples of what can be expected in the coming years.

This is already observed when comparing two results of the Solution Exploration. When comparing the average Client profit for the cases with 40 and 80 satellites, regions with multiple optimal values appear (Figure 5-15a, Figure 5-17a, Figure 5-19a and Figure 5-21a) which are related to the competition between Clients. With more satellites, it is likely that more than one Client will request servicing around the same time. Additionally, for longer extensions in life (>40%) the Servicer might become less available or run out of resources more quickly. These are examples of conditions that can affect directly the results, explaining the difference between the results.

This reinforces the need to consider Client a Servicer concurrently when evaluating OOS. The rearrangement of the launch time or simply the change of the servicing time could represent an improvement in the overall profit of a Client fleet and better resource management from the Servicer side. This capability of the model helps the user to tailor its systems to meet a specific demand or to take advantage of a possible resource, while considering the counterpart, another model requirement.

As it was presented in the model description and highlighted by the results, the many parameters relevant to the problem and their effect on the system can be difficult to estimate at first. The Solution Exploration feature allows the combination of specific parameters to facilitate the definition of those inputs. In the results presented a total of 5929 combinations were simulated for each satellite of the fleet, presenting the conditions that can be more attractive to the user. This helps to identify conditions that might be beneficial for both Client and Servicer, suggesting the parameters the user can focus on and help to resolve possible conflicts as discussed earlier. Still, further work is expected in the definition of a more advanced mode of solution exploration.

Characteristics such as penalties or simplified decision attributes for Servicer or Client can improve the definition of parameters to individual agents, instead of a fleet solution. As the current version of the model limits the Solution Exploration to a single Servicer for the Client fleet, the points mentioned can also allow the consideration of multiple Servicers.

It is important to note that the solution exploration iterates the factors for the entire fleet at once, working as a snapshot of the possible cases of servicing under given conditions for the fleets. From a concurrent engineering point of view, it is important to consider how the changes in one of the sides (Servicer or Client) can affect the other. The exploration of individual optimal conditions is not the current objective of this part of the model, however, the implemented features allow this functionality.

The inclusion of an optimisation routine would demand the definition of additional parameters, mainly related to scheduling and operations time. For example, the optimal condition of a given Client satellite might affect the optimal condition of another satellite (being serviced earlier or later). A Servicer in charge of a longer servicing time (relevant to *Lifetime Extension* cases) will have less availability, which can be detrimental to other Client satellites of the fleet. Therefore, the optimisation must be considered individually from Client and Servicer perspective which can lead to the analysis of both results to identify a “concurrent optimal”.

The OOS applications included in the model are those which are currently pursued commercially. Extension of life, maintenance and response to failures are the basic areas that can enable further types of servicing of more complexity. Having this modelled also gives the user other means to make decisions at early stages of the design and procurement. The application of *Payload Augmentation* is one of the promising solutions to be provided by OOS. However, the current model capacity is limited by the information related to hosted payloads and different academic and industrial proposals with different technology readiness levels. As more concepts are demonstrated and more information become available, the model will be refined. Understanding the basic characteristics of the payloads to be installed, such as mass, cost and operation, will lead to an improved representation of how the metrics are affected by the installation of the additional subsystem.

Finally, it is important to highlight the reasons for the implementation of the framework mainly focused on GEO environment. As part of the framework requirements of considering the main current commercial servicing options, the demonstration in this chapter was limited to GEO constellations. Virtually, the framework could be applicable also to LEO and, with minor additions, to MEO. However, the current available information regarding servicing on those last two environments is limited.

As the framework intends to establish the link between Client and Servicer, its basic structure as presented in this chapter can address an initial analysis for LEO (and MEO) cases. This would require the user to have a proper established scenario and information of the Client and Servicer sides, LEO and MEO cases could be simulated.

From an organizational perspective, a reasonable proposition would have to be defined regarding non-GEO cases. For example, concepts of universal Servicer and servicing on demand from and to different orbits can be arguably difficult to demonstrate in real life cases. Definition of targeted applications and Clients, as well as business models make broader and more difficult the exploration of these cases. The points observed in Chapters 2 and 3 are examples of the cautious views of some operators in adopting OOS.

Technically, the use of resources related to LEO environments can be more aggressive considering changes in inclination/orbital planes and orbits in general. A Servicer operating in a LEO environment would have to consider a more rigorous approach to the resources for servicing operations, reflecting on servicing costs and acceptance/attractiveness to the Client operator (cost-benefit). These are points affecting directly in a proper high-level definition of a servicing proposition, at an organization level, in these environments.

Also, as demonstrated in Chapters 2, the main immediate uses of OOS solutions are likely to happen in GEO environment. This is expected to generate more information of concepts of operation, acceptance and attractiveness that could be used again in the refinement of the modules presented in this chapter. Additionally, the practical execution of servicing will likely attract the attention of other operators, not necessarily commercial, or in GEO orbits. Then, more reasonable cases of LEO and MEO applications could be properly defined and simulated in the framework. However, even in the current version of the implementation, the framework still allows the first steps in the relation of Client and Servicer to be strengthened.

Despite being focused on GEO due to the reasons discussed previously, potential cases of framework use for non-GEO scenarios are discussed with more details in Chapter 6 and Chapter 8. Cases of the potential use of the framework for non-GEO scenarios are mainly related to the current trend of using large LEO constellations and concerns with debris.

5.6 Conclusions

This chapter presented a model to represent the concurrent relation of Client and Servicer in an On-Orbit Servicing context. The main servicing applications considered are those being currently pursued by different commercial players.

The main requirements were defined for the modelling and later verified and demonstrated in the results. Even though different methodologies could be used, Agent Based Modelling and Simulation was the main methodology used due to the capacity to characterise the relation of agents in an environment and their behaviour over the time. The model was implemented in Excel/VBA and was arranged modularly to allow the interchange of modules for future needs.

The results presented helped to illustrate the effects of different types of servicing and their effect on the Client and Servicer operation. The results also helped to highlight the concurrency of this area and the need to consider Client and Servicer simultaneously when exploring OOS.

The solution exploration features expanded the capacity to account for a large number of solutions in order to identify possible optimal or attractive conditions from the side of Client, Servicer of both. Such characteristics are not observed in the current published research and represent a powerful tool for systems and concurrent engineers to employ at early stages of the design and procurement.

The model allows the user to explore OOS which, despite being thoroughly researched in many aspects, presents challenges in the implementation as a normal practice of space engineering. In parallel with other developments in OOS, the model helps to establish the link of the two sides of this area in a concurrent manner.

6 OOS Framework

With the mathematical core of the framework defined and its functionality verified, this chapter presents how such framework is used based on real-life operators. The main contents of this chapter have been published in Acta Astronautica [144].

6.1 Context

For the demonstration, the case for a hypothetical satellite operator is explored, under a specific set of requirements and conditions for different servicing solutions. The basic assumptions of Client, Servicer and servicing operations are discussed, and the initial simulation parameters are defined. The ABMS is used to simulate OOS for a fleet of geostationary communication satellites for the cases of *Lifetime Extension*, *Refuel* and *Rescue and Recover*. In the end, the outputs are used to explore the design aspects of the Servicer and Client satellites at systems level. The results highlight the advantages of having this type of framework for early assessment of OOS under different types of context for both Servicer and Client. The chapter concludes with directions of how the framework can be used to explore more complex and realistic scenarios of OOS and assess their potential benefits.

6.2 Methodology

6.2.1 Satellite Operator and Fleet Requirements

A hypothetical case is considered here, to exemplify the use of the framework. The case considers an operator with a given fleet of geostationary communication satellites.

The three largest operators of GEO communication satellites (SES, Intelsat and Eutelsat) are used as a reference to define the fleet for this case. Characteristics such as orbital position, mass, satellites launched per year, and design life are extracted from the SpaceTrak database [168]. The sample has 124 satellites from all the three operators. The filters and options to collect the sample of satellites are defined in Table 6-1.

Table 6-1 – SpaceTrak filters and options

Filter	Options
Operator	SES S.A., Intelsat, Eutelsat S.A.
Launch Date	From 01/01/2000 to 31/12/2017
Event Type	Launch – Successful
Sector	Commercial
Orbit Category	GEO
Spacecraft Status	Active

A total of 30 satellites (Table 6-2) are selected from the sample to compose the hypothetical operator fleet, representing a medium size fleet.

The ΔV is estimated using total mass, design life and propulsive characteristics. Assuming a GTO to GEO transfer, a ΔV ranging from 1.5 km/s [63] to 3 km/s [161], depending on the propulsion type (chemical or electric), is considered and subtracted from the total ΔV calculated. The remaining ΔV is considered available for station keeping during the designed life.

Satellites' costs as new (including launch) are extracted from the SpaceTrak database when available, or calculated using cost estimating relationships (QuickCost and USCM8 [63]). Actual values can also be directly entered by a user if they are known.

The beginning of operation time is defined by checking the time the satellite was launched. All the satellites from the sample are sorted and the time is counted from the first Client satellite launched.

Orbital slots for Client satellites considered are illustrated in Figure 6-1. The inclination is also included in the simulation despite being extremely small (not higher than 1 degree). However, the values are not presented here due to the minor relevance to this specific case.

Table 6-2 summarises the satellites' characteristics for the Client fleet.

Table 6-2 – Client fleet parameters

ID	Total Mass [kg]	Mass On Station [kg]	Op. start [year]	t_{life} [years]	Cost [FY2018 M$]	ΔV On Station [km/s]	Prop. Orb. Insert.	Prop. Station Keep.
1	2784.0	1751.3	0.0	15	195.12 [CER]	0.818	BP	MP
2	4021.0	2529.5	8.1	15	255.57 [CER]	0.818	BP	MP
3	2649.0	1666.4	0.4	15	205.28 [DB]	0.818	BP	MP
4	2473.0	1555.7	11.9	16	180.29 [CER]	0.872	BP	MP
5	3903.0	2455.3	3.2	15	249.58 [CER]	0.818	BP	MP
6	1720.0	1082.0	2.1	12	152.12 [CER]	0.654	BP	EP
7	3901.0	2454.0	4.1	15	249.48 [CER]	0.818	BP	MP
8	1983.0	1247.4	4.0	15	158.24 [CER]	0.818	BP	MP
9	2015.0	1267.6	4.3	15	159.69 [CER]	0.818	BP	MP
10	4100.0	2579.2	6.7	15	273.49 [CER]	0.818	BP	EP
11	4332.0	2725.1	9.6	15	271.65 [CER]	0.818	BP	MP
12	3643.0	1894.8	4.8	15	241.02 [CER]	0.818	MP	EP
13	4385.0	2758.5	11.2	15	274.42 [CER]	0.818	BP	MP
14	2845.0	1789.7	1.0	15	197.99 [CER]	0.818	BP	MP
15	5922.0	3725.4	12.6	15	380.81 [CER]	0.818	BP	EP
16	4144.0	2606.9	0.0	15	275.9 [CER]	0.818	BP	MP
17	2205.0	1892.3	18.5	15	158.13 [DB]	0.818	EP	EP
18	2221.5	1906.4	19.8	15	158.13 [DB]	0.818	EP	EP
19	2500.0	1572.7	3.6	10	183.79 [CER]	0.545	BP	MP
20	5053.0	3178.7	9.3	16	327.76 [CER]	0.872	BP	EP
21	3551.0	3047.3	20.7	15	271.63 [DB]	0.818	EP	EP
22	4484.0	2820.8	3.3	15	294.77 [CER]	0.818	BP	EP
23	1760.0	1107.2	6.6	15	148.19 [CER]	0.818	BP	MP
24	4060.0	2554.0	7.1	15	271.31 [CER]	0.818	BP	EP
25	2087.0	1312.9	8.9	15	162.96 [CER]	0.818	BP	MP
26	2033.0	1278.9	9.1	15	261.63 [DB]	0.818	BP	MP
27	5493.0	3455.5	8.8	15	353.98 [CER]	0.818	BP	EP
28	4850.0	3051.0	5.8	15	315.66 [CER]	0.818	BP	EP
29	3300.0	2075.9	19.0	16	224.25 [DB]	0.872	BP	EP
30	2350.0	1478.3	11.3	15	174.97 [CER]	0.818	BP	MP

[DB] Costs extracted directly from SpaceTrak database and corrected for FY2018

[CER] Costs calculated by the framework using Cost Estimating Relationship

The compatibility for each Client satellite is defined as:

- *Lifetime Extension*: Clients 6, 10, 12, 15, 18, 20, 21, 22, 24, 27, 28 and 29.
- *Refuel*: Clients 1, 2, 3, 4, 5, 7, 8, 9, 11, 13, 14, 19, 23, 25, 26 and 30.
- None: Clients 16 and 17.

Considering the population of Clients presented in Table 6-2, Clients are selected for *Lifetime Extension* based on their propulsion type for station-keeping. The current methods for refuelling of propellants for electric propulsion (e.g. xenon gas) are limited or under development, based on the servicing options offered commercially. Therefore, for the case explored herein, *Lifetime Extension* is assumed to be the only option to extend the life of satellites using electric propulsion. The remaining Clients of the population are assigned defined with *Refuelling* compatibility. The two Clients defined without any servicing compatibility are selected randomly from the population.

For the case of emergency servicing (*Rescue and Recover*) all the Client satellites are assumed to be compatible with the Servicers.

6.2.2 Servicer Fleet and Simulation Conditions

Based on the main developments presented in Section 1, parameters are defined for each type of Servicer (Table 6-3).

Table 6-3 – Servicer parameters

Type	Total Mass [kg]	Mass On Station [kg]	t_{life} [years]	Cost [FY2018 M$]	ΔV On Station [km/s]	Prop. Orb. Insert.	Prop. Station Keep.	Sellable Propellant Mass [kg]	n_s
Rescue and Recover	1680.49	1057.15	20.00	172.48	1.090	BP	EP	-	1
Lifetime Extension	1862.18	1171.44	20.00	179.01	3.104	BP	EP	-	1
Refuel	5054.78	3179.81	15.00	329.97	0.818	BP	EP	1250 (MP)	1

For *Lifetime Extension* the Servicer operators must consider the expected mass of the Client being serviced when designing their systems. It is important to note that the ΔV requirements for station keeping are still the same (around 50 m/s per year); however, the total mass of Servicer-Client system will require more propellant mass for the station-keeping manoeuvres. When such required propellant mass is considered for the Servicer mass alone, a higher ΔV capacity is presented as it can be noticed in Table 6-3, Figure 6-3a (ΔV) and Figure 6-3b (propellant mass).

For planned operations (*Lifetime Extension* and *Refuel*) the starting time and orbital slot for the Servicers are based on the first serviced Client. For emergency operations (*Rescue and Recover*) the Servicers start the operation at the first year of the simulation, in pre-defined orbital slots. The ΔV estimation for the Servicers follows the same method used for the Clients, considering apogee burn for GTO to GEO transfer. Table 6-4 presents the main parameters considered for the simulations proposed.

Table 6-4 – Simulation Parameters

Parameter	Value	Rationale/Remarks
Simulation time	30 years	-
Standard Weibull θ	69112.52 years	(Appendix F)
Standard Weibull β	0.3607	(Appendix F)
Servicer Weibull θ	8338.49 years	Based on Saleh [165]
Servicer Weibull β	0.3874	Based on Saleh [165]
Standard *TTBE*	40% of Clients' design life	Estimation based on Graham [28]
Standard Discount Rate (*r*)	6%	Estimation based on Graham [28]
Standard extension of life	30% of t_{life} for *Refuel.* 15% of t_{life} for *Life. Ext.*	Based on services from Table 2-3
Life limit for servicing	At 70% t_{life} for *Refuel.* At 50% t_{life} for *Life Ext.*	For *Refuel* and *Lifetime Extension*
Cost of servicing (servicing charge)	1.232 M$ per kg [a] (Life. Ext.) 0.166 M$ per kg [a] (Refuel.) 3.169 M$ per kg [a] (Resc. Rec.)	Based on the Servicers' cost and sellable capacity/consumable resources [b]
Critical satellite value	1% of the total Cost as New	Point at which satellite is considered to be of no real value
Maximum failure rate	5 failures per year[c]	-
Number of runs for *Life. Ext.* and *Refuel.*	1	-
Number of runs for *Resc. and Recov.*	10	-

[a] Price applied to the kg of resource spent by the Servicer in the entire servicing operation, independent of the application. It considers the propellant spent in the phasing manoeuvre ("delivery"), propellant spent in rendezvous and proximity operations, propellant transferred (if *Refuel*) and propellant spent in station keeping (if *Lifetime Extension*).

[b] The cost of servicing considers the Servicer cost, the available resources (propellant) for the manoeuvres and servicing tasks and the sellable propellant for refuelling. This is a threshold cost estimated to give a break-even condition for the Servicer at a given time (the end of life for the example presented herein).

[c] The maximum failure rate used in the stochastic generation of failures is a constraint used by the framework to limit the maximum number of failures allowed to happen in one year of the simulation. However, the value defined does not represent that this number of failures will necessarily happen, as it will be presented in the results. The values used herein are a simplified approximation based on failures identified in SpaceTrak Database. This is a parameter defined as desired by the user.

With exception of Simulation Time, all the simulation parameters presented in Table 6-4 are considered as individual characteristics of each Client and Servicer satellite. For the purpose of this demonstration though, they are considered the same for the whole Client fleet. It is important to note that all the parameters from Table 6-2, Table 6-3 and Table 6-4 are expected to be defined by the user/users (Client, Servicer or both) when using the framework in a real case. Since the detailed definition of each parameter would require more extensive information about the user-specific concepts of operation, business plans and heritage knowledge, the values used herein are estimates for the demonstration of the framework. The sensitivity of the simulation to different set parameters is covered in Chapter 7 with the use of Solution Exploration and the different use cases.

As previously mentioned, for the *Refuel* application the Servicers can be refuelled once they are moved to a refuelling base. Such a base is defined in an orbital slot considered of small commercial interest for geostationary operators. Therefore, the base is considered at the longitude of 170 degrees West (mid-Pacific Ocean). The base is considered static at that position and the Servicers will move to it when it is required. The positioning of the base over a more favourable area would be beneficial for the Servicer as well as the use of multiple bases which is allowed by the framework. However, since the discussions about the use of a fuel depot in orbit are still in early phases when compared to the development of the current servicing systems, in the demonstration of the framework the base is positioned in an area with less commercial value per slot to avoid having to expand more in other aspects of this (legal, political, financial).

In Figure 6-1 is also illustrated the location of the Base for refuelling of the Servicers.

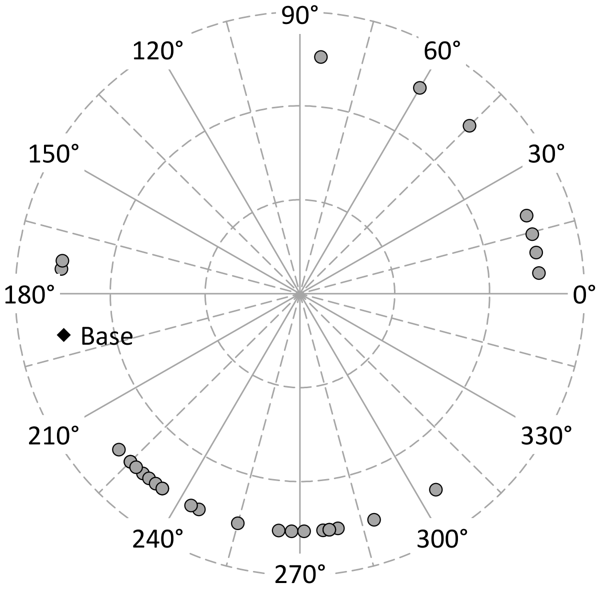

Figure 6-1 – Longitudinal location [11] of Clients and Base

6.3 Results

As previously discussed, the interaction of Clients and Servicers is not trivial, which reflects the complexity of analysing OOS scenarios. When considering a large fleet this complexity becomes more evident, with multiple metrics to be analysed for multiple satellites. For this reason, an example of each servicing case is isolated from the general results and presented in this section for discussion. In Figure 6-2 are presented isolated results for the cases of *Lifetime Extension* and *Refuel*. In Figure 6-5 are presented the isolated results for *Rescue and Recover*. In both figures are presented at least one satellite that was not serviced. In the individual results it is possible to check more clearly the effects of servicing in each of the metrics which are discussed as follows.

6.3.1 Lifetime Extension and Refuel

For the case of planned servicing, the Servicer fleet received 28 requests for servicing of which 22 were effectively serviced. This highlights the characteristic of availability and compatibility of the Servicer fleet.

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[11] The longitudinal position of the GEO satellites comes from the data from SpaceTrak database.

An example of a satellite that was not serviced is also presented by the curves in long-dashed lines. Such a condition could have occurred due to Client incompatibility or unavailability of the Servicer (which could be either servicing another Client, refuelling itself at the Base, or dead). Indicated by the short-dashed lines are the periods of the simulation in which the satellites are not operational, i.e. the values of the metrics are not being calculated or used by the framework.

The effects of *Lifetime Extension* and *Refuel* can be noticed respectively by the green and blue curves in Figure 6-2. For more clarity in the results, Figure 6-2 illustrates only the first 18 years of the 30-year simulation with Client 6, Client 16 and Client 19 starting their operations at different times through the simulation. In the example, while both Client 6 and Client 19 operate for a longer period than the original design life, there are differences in how the life extension happens.

Looking at the ΔV curves (Figure 6-2a), it is possible to verify the condition that maintains the Servicer attached to the Client 6 for the *Lifetime Extension* case. The Client ΔV consumption stops for the period of life extension and, after that, the Client continues to use its own fuel towards the end of operation. During the servicing time, the Servicer is in charge of station keeping and orbital corrections, which can be verified in Figure 6-3a, Servicer 1 (green curve). Still looking at the ΔV, the Client 19 is refuelled around year 11 of the simulation. For this case the ΔV is recovered due to the refuelling and the Client continues to operate using its own means, allowing the Servicer to be assigned to other servicing operations. The extension in life provided by these two types of servicing will consequently change how the other metrics degrade with time. Figure 6-3b shows the effects of servicing on the propellant mass of the Client; note that propellant mass is low in the case of Client 6 due to the use of electric propulsion on this satellite.

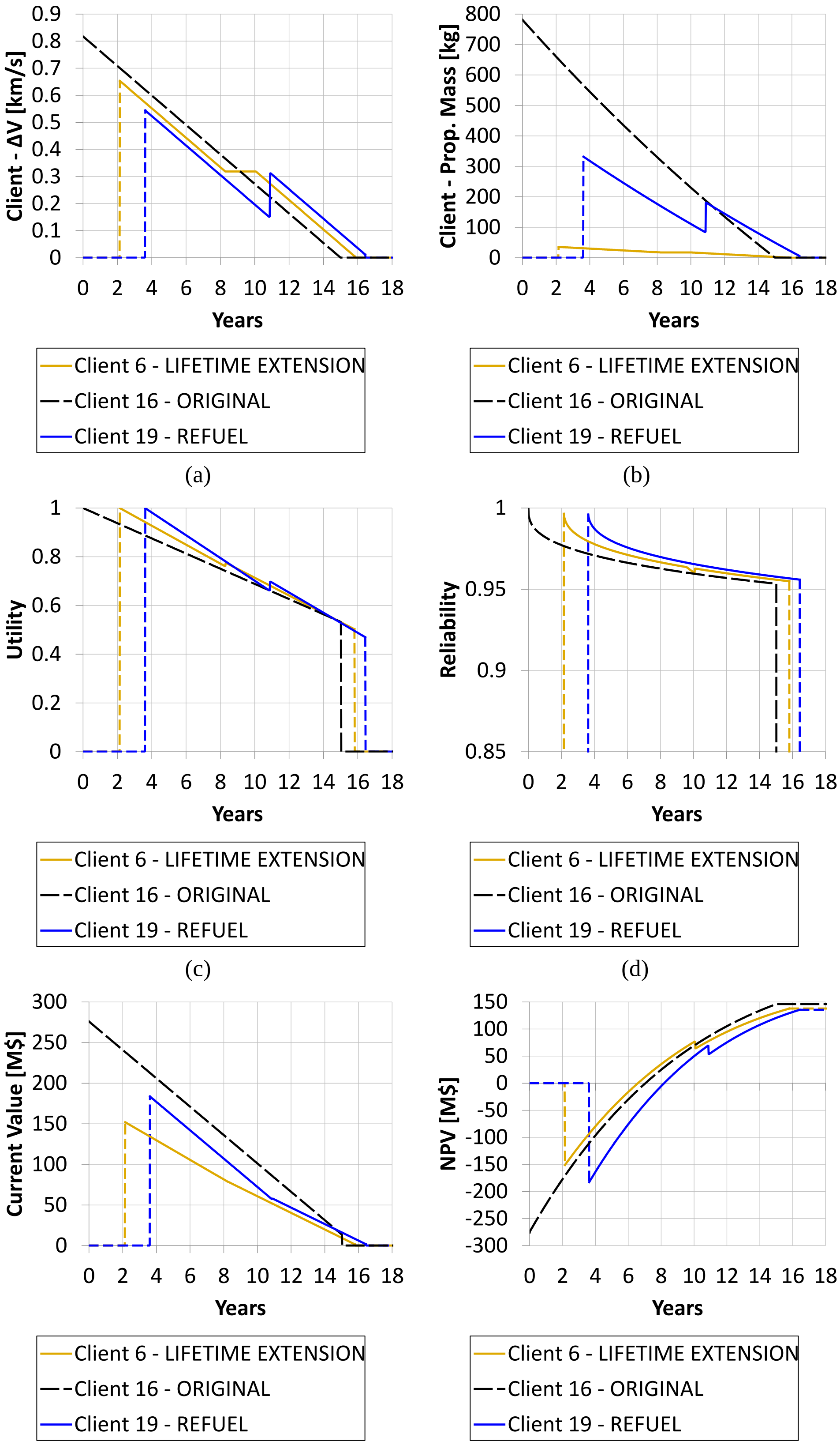
For this chapter, *Utility* is considered as a simplified linear function as opposed to the function presented in the previous chapter. The reason is due to the suggestions made by industrial reviewers interested in the demonstration of the main financial metric (*NPV*) due its major importance in a commercial environment. Additionally, discussions with representatives of a large commercial satellite operator throughout the research highlighted the focus on the *NPV*, with a more simplified approach of the system obsolescence. Looking at the *Utility* curves (Figure 6-2c), Client 6 and Client 19 recover a portion of its *Utility* due to extension of the operational life. As discussed in the previous chapter, and will be demonstrated in Chapter 7, the recovery in the *Utility* metric can be limited based on when the servicing operation happens and how many times a Client is Serviced. This indicates that, even though the Client has the same amount of fuel replenished twice, there will be a point at which servicing will no longer be attractive, as the *Utility* continues to reduce.

The *Reliability* parameters used for this simulation came from a sample of geostationary satellites launched between the years 2000 and 2017 (Appendix F), using the method presented by Castet and Saleh [165]. Regarding the extended life, even though the systems have longer operational life after servicing, no drastic changes are noticed due to the high reliability of the systems as can be seen in Figure 6-2d. However, it is also noticeable how *Reliability* is affected during the periods when the Servicer is attached to the Client. For Client 19, due to the time spent refuelling (between one and two weeks [169]) the *Reliability* drops for a fairly short time. This effect is more evident for Client 6. During the extension time, the Servicer is docked to the Client creating a “third system” with different characteristics for mass, dynamics and operation. One trade-off that has been discussed about OOS is related to the possible savings of relaxing systems requirements, which will then affect directly how the reliability curve degrades. Even though the framework allows exploring this trade-off, such analysis would go beyond the scope of the current chapter.

The *Current Value* (Figure 6-2e) also has a clear effect from servicing. Once the satellites have their life extended, the degradation, or how the current value reduces, has a change in the slope, allowing the operator to keep the satellite value for a longer time. However, similarly to what was discussed for *Utility*, there will be a point in which the *Current Value* of a satellite will be low enough that another servicing mission could not be justified.

Finally, in Figure 6-2f is presented the Clients’ capacity for money generation with time. As described before, it uses the *NPV* based on stakeholder requirements/characteristics to represent it. Most important, it highlights the effects of servicing as the Client operator pays for it, indicated by the discounts in Client 6 and

Client 19 *NPV* after year 10 of the simulation. The main parameters defining such charges from the Servicer perspective are the resources used, in this case fuel and time spent and fuel transferred for refuelling cases. For Client 6, this happens before year 10 when the extension is completed. Client 19 is charged around the same time after the operation is completed. For this metric, in addition to the concept of time value of money, the system degradation with time and how it reduces the capability of revenue generation towards the satellite life is also considered; this is mainly indicated by the curves going “flat” with time. Concurrently with the other metrics presented previously, the framework can be used for trade-offs regarding when to request a service, for how long the life should be extended and which type or servicing should be used. After the end of the operational life, *NPV* is presented as a constant straight line, indicating the maximum value the satellite operator could get from that satellite.



(a) (b) (c) (d) (e) (f)

Figure 6-2 – Isolated Results – Client metrics – (a) *ΔV*, (b) On Station Propellant Mass (c) *Utility* [*U(t)*], (d) *Reliability* [R(*t*)], (e) *Current Value*, (f) *NPV*

Looking from the Servicer perspective (Figure 6-3), ΔV, propellant masses and *NPV* are presented for the entire simulation period (30 years). Servicer 1 and Servicer 2 started the operation respectively after the year 5 and year 10 of the simulation, prior to their first servicing operations.

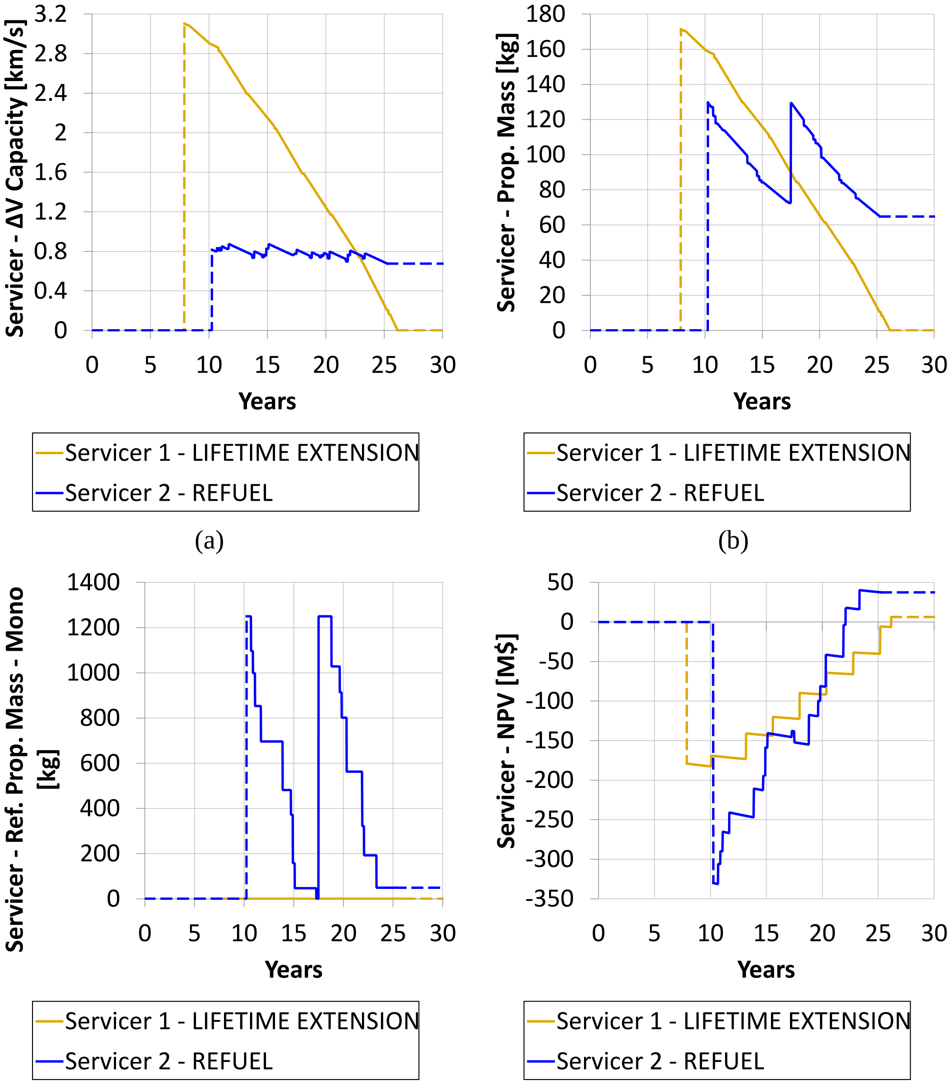
From Figure 6-3a and Figure 6-3b it can be observed the decrease of ΔV capacity and the available propellant for manoeuvre and station keeping. Each slope period followed by a small drop in Figure 6-3b represents respectively the periods of station keeping and phasing/servicing manoeuvres. Servicer 2 was considered refillable for both sellable propellant and usable propellant, and the occurrence of such an operation can be observed around year 17. In addition to replenishing its tanks of sellable propellants, it also refuels its propellant for general operations, thus being able to operate through its entire design life (15 years).

The minor steps-up observed in Figure 6-3a for Servicer 2 are linked to the Client refuel operations. Since the sellable propellant is considered as a payload and not as usable propellant for the Servicer, each refuel operation reflects in release of mass from the Servicer. However, the available propellant for manoeuvres and station keeping is not consumed for any other task but the phasing manoeuvre as observed in Figure 6-3b. This results in a higher ΔV capacity at each operation and less propellant consumption for manoeuvres and station keeping observed respectively by the steps-up in Figure 6-3a (Servicer 2) and changes in the curve slope in Figure 6b (Servicer 2).

Servicer 1 has a different concept of operation, moving from one Client to the other and staying for a longer period at each one, in charge of the station keeping manoeuvres. This limits the number of Clients serviced, as presented in Figure 6-3a and Figure 6-3b. Additionally, the concept of a “third system” discussed previously changes how the Servicer consumes its propellant mass. Since the propulsion system is in charge of thrusting a much larger mass (Servicer and Client), it consumes propellant more rapidly, as noticed by the changes in the slope for the green curve.

Figure 6-3c presents the sellable propellant mass of mono-propellant. From a Servicer perspective, this capacity should be driven by the possible demands of Client refuelling in order to define a proper system and operation concept for refuelling.

Figure 6-3d presents the Servicers' *NPV* with time, based only on completed servicing operations. Servicer 1 revenue was around 189M$ while Servicer 2 recovered at least 367M$ from its operations. Since the Servicer perspective used in this chapter assumed a servicing cost just enough to break-even, the profits from the Servicers were limited. Additionally, the example assumes only one medium size satellite operator which restricts the possible demand for servicing. Other characteristics such as Servicer life and capacity are directly relevant for the exploration of higher profit cases. This highlights the usefulness of this framework relating Servicer and Client, from a Servicer perspective. Fleets from different operators and different sizes can be used as inputs to explore servicing demands and planning.



(a) (b)

(c) (d)

Figure 6-3 – Servicers metrics – (a) ΔV, (b) On Station Propellant Mass, (c) Sellable Propellant Mass – Mono-propellant, (d) *NPV*

Finally, in addition to the general metrics results, the framework is able to compare each metric for conditions with and without servicing. Such comparison considers how each Client performed over its designed life and how the same satellites performed over serviced life, if serviced. This can be used to evaluate how attractive or beneficial the servicing operation is, providing direct outputs for decision making process.

The percentage indicated in the comparison is relative to the operational life of the satellite without using any servicing. In addition to the potential improvements in the operational life, the comparison also accounts for the potential drawbacks when using servicing, e.g. payment for the Servicer, affected *Reliability* and *Utility* by the presence of the Servicer. Therefore, any value above zero would represent a potentially attractive option in using servicing, while the opposite, negative values, would demonstrate that servicing might not be attractive. Furthermore, as it will be demonstrated in the results, the comparison can illustrate conditions in which servicing would be attractive only a given perspective (technical perspective or financial perspective).

As an example, Figure 6-4 presents the comparison of *NPV* and *Reliability* for two serviced Client satellites. The figure illustrates the results the stakeholder would analyse before committing to any decision of servicing or not, one of the main objectives of this framework.

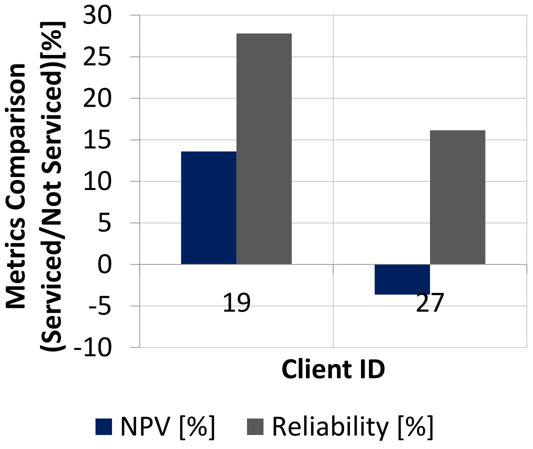


Figure 6-4 – Servicing Comparison – Example for *NPV* and *Reliability*

With results such as the presented in Figure 6-4, the user would have the means for choice to service or not. In the presented case, servicing is presented as a potentially attractive option for Client 19 as both *NPV* and *Reliability* present positive values for the comparison to the operational life without servicing. However, the negative value for the comparison of *NPV* for Client 27 demonstrates that in this case it would not be commercially advisable for the Client operator to proceed with such a servicing strategy. Still, the comparison of *Reliability* for Client 27 shows positive values. Hypothetically, for the case of an operator not strictly commercial, the operator could use the presented results to analyse if the benefits in *Reliability* represent a higher impact in the operation (using servicing), justifying the drawbacks in *NPV*.

6.3.2 Rescue and Recover

For the case of emergency servicing, 10 instances of the simulation were run due to the aleatory/stochastic nature of the failure operator. In each instance, different numbers of servicing requests were generated and effectively serviced as presented in Table 6-5. In the same table are presented for each run the effective rate of failure (number of servicing requests divided by the simulation time) as well as the probability of failure for one of the 30 Client satellites of the fleet (effective $rate_{failure}$ divided by the number of Client satellites). As described before, the failure rate ($rate_{failure}$) presented in Table 6-4 is used as a constraint of the maximum possible failures in one year of the simulation. The effective rate of failure verifies that the failures generated in a non-deterministic way are below the value defined for the simulation.

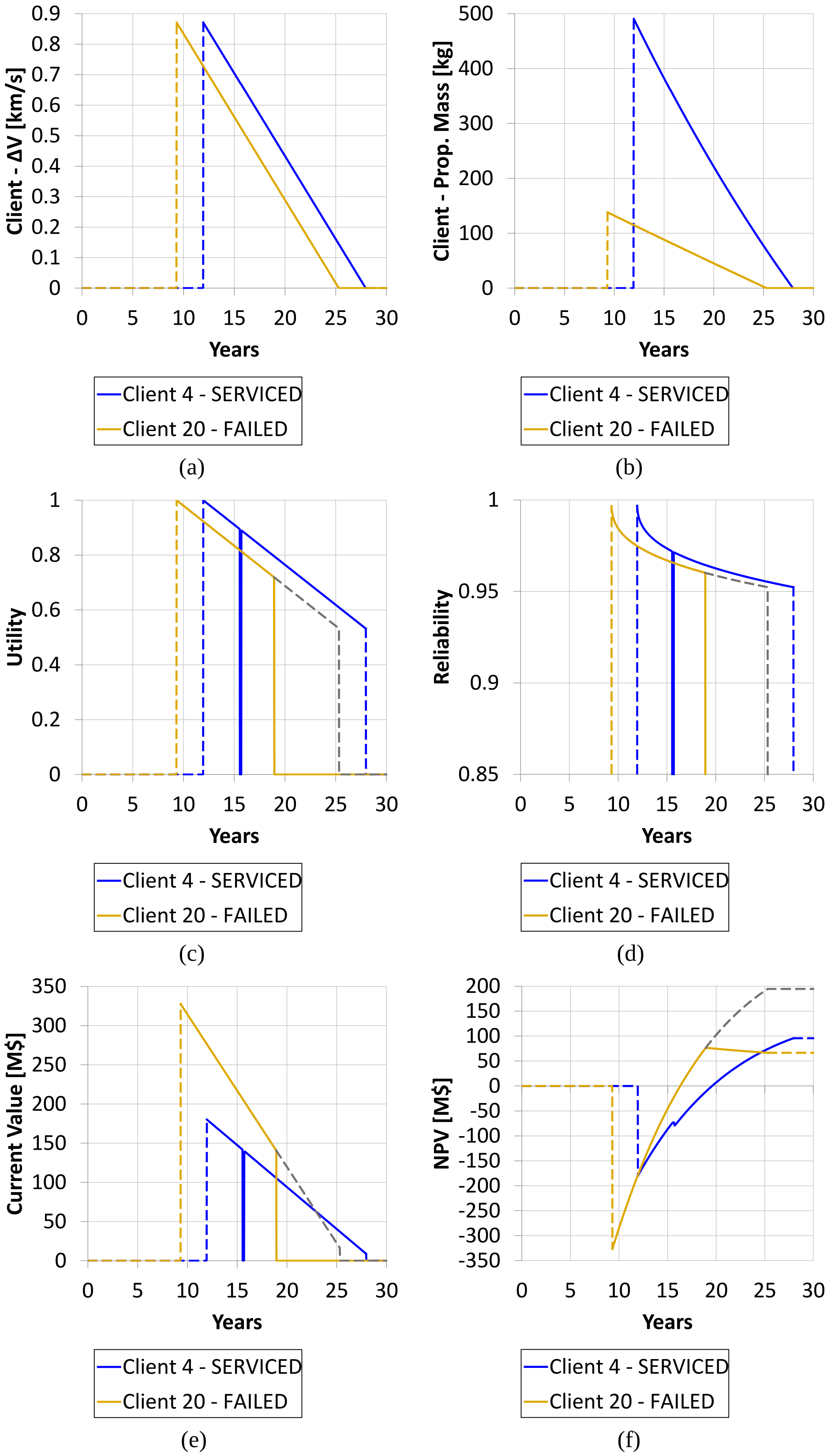
Once more, selected results were isolated from the whole fleet for an example. The same metrics discussed before are presented in Figure 6-5, showing the results generated from simulation 10. For clarity, the figure presents only the results for a Client that was serviced (Client 4) and a Client that was not serviced (Client 20). Client 4 suffered one failure through the simulation after year 15. For Client 20, after the failure after year 19, a dashed line is used to illustrate how such satellite would continue the operational life if a failure did not occur.

Table 6-5 – *Rescue and Recover* – Servicing request and servicing operations

Run #	Servicing Requests	Servicing Completed	Effective $rate_{failure}$	Client fail. probability
1	9	6	0.30	0.010
2	6	5	0.20	0.007
3	6	4	0.20	0.007
4	13	8	0.43	0.014
5	9	8	0.30	0.010
6	8	8	0.27	0.009
7	10	5	0.33	0.011
8	8	7	0.27	0.009
9	9	5	0.30	0.010
10	10	8	0.33	0.011

A few assumptions/simplifications are defined for the current example otherwise more specific details would have to be discussed. Yet, the framework can address such aspects in a detailed analysis.

First, since the failures are not considered in one particular subsystem for this specific case, it is assumed that, once a Client satellite failed, the operator is not able to commercially use the satellite anymore. For this reason, the failure is assumed to not affect the ΔV and propellant mass, which explains why no changes are presented in this metric (Figure 6-5a and Figure 6-5b). On the other hand, the other metrics are affected. *Utility* and *Reliability* is considered as zero once a Client fails and the operator is not able to use the satellite anymore. Since the satellite is temporarily unusable, no income is generated and *NPV* decreases due to costs with operations and ground segments (Figure 6-5c and Figure 6-5d). Considering the *NPV* decrease, it would be up to the operator to decide whether to continue using the satellite, paying for the costs with operation without having an income from that satellite.



(a) (b)

(c) (d)

(e) (f)

Figure 6-5 – Isolated Results (*Rescue and Recover* run #10) – Client metrics – (a) ΔV, (b) On Station Propellant Mass, (c) *Utility* [*U(t)*], (d) *Reliability* [R(*t*)], (e) *Current Value*, (f) *NPV*

This state will continue until the Servicer is assigned and completes the phasing and servicing. The assignment, orbital phasing and servicing take place on a timescale much smaller than the 30 years of the simulation, the reason why this failure interval is not evident in the graphs. An example is presented in Figure 6-6, illustrating the simulation between years 11 and 18, when Client 4 starts the operation, fails and is serviced between years 15 and 16.

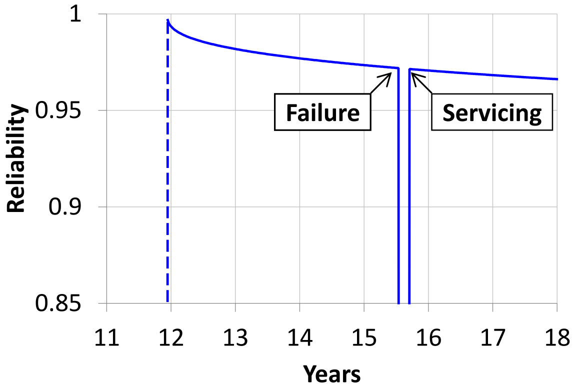
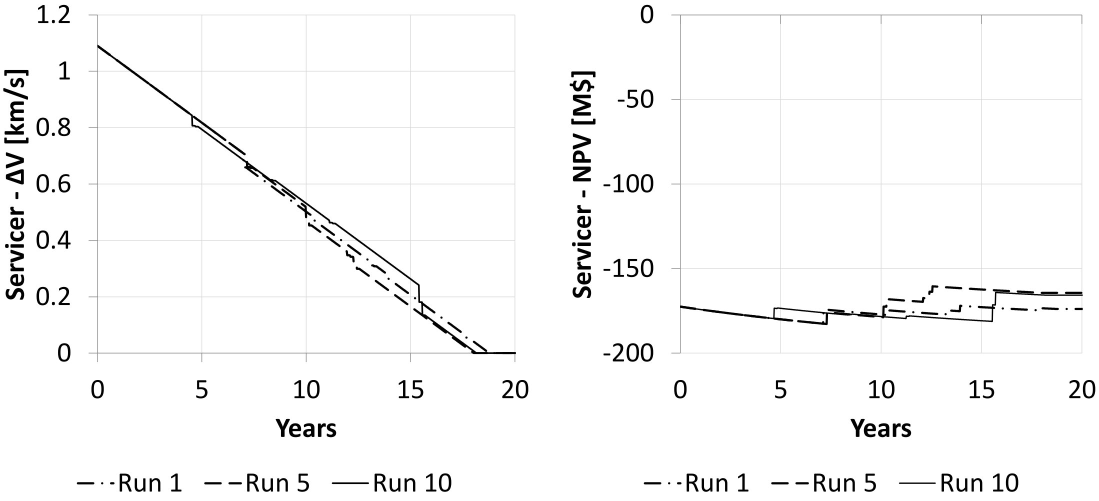


Figure 6-6 – *Rescue and Recover* – *Reliability* – Detail

Another assumption considers that, after servicing, the metric is recovered to the level expected for that point in the lifetime. A further refinement in the failure mode could characterise the failure of a subsystem, reflecting in a partial loss of the metrics affected, instead of zero.

Regarding the servicing charges, for demonstration purposes, only consumables are used to calculate the servicing cost. However, the framework allows the use of additional factors and costs depending on the characteristic of the operation, such as responsiveness and dexterity needed, and the Servicer itself (business model).

Unlike the case of planned servicing, in the *Rescue and Recover* case it is not possible to set the Servicers to start at one specific time and position when simulating failures in a stochastic/random manner. This reflects in an idle Servicer, spending resources while no servicing requests are generated, as shown in Figure 6-7. In the figure are presented the results for three different simulations for the visualisation of how a Servicer can be requested at any specific time. Each drop in the *ΔV* curve (Figure 6-7a) represents one manoeuvre of the Servicer to respond to a Client failure and can be checked concurrently with Table 6-5.



(a) (b)

Figure 6-7 – ***Rescue and Recover*** **– Servicer** ***ΔV and NPV***

Due to the high reliability and redundancy of space systems nowadays, the case for *Rescue and Recover* represents a challenge from the Servicer point of view, as it can be observed in Figure 6-7b. A Servicer aimed for failure remediation should be able to do other tasks in order to be cost efficient. This is already observed in one of the future servicing missions to be launched [45] in which the Servicer is designed not only for failure corrections but also refuelling. As discussed before other factors can be included in the consideration of servicing costs, highlighting another use of this framework.

As previously mentioned, the use of more relaxed Client satellite requirements could be enabled by servicing, especially for the case of *Rescue and Recover*. This could be simulated in the framework by using different parameters for *Reliability* and for failure rate. Then this could be a case to be discussed between Servicer and Client operators that would justify servicing satellites exclusively for failure remediation. From the Client operator point of view, a more relaxed design could represent savings in time and cost for the development of satellites. Ellery et al. [58] explore, among other points, the role of high-reliability for different satellite platforms, bringing important guidelines that can be used to simulate more detailed cases of *Rescue and Recover*.

6.4 Discussion

With the results of this framework it is clear there is a need to consider different metrics of the system to analyse the case of OOS; it is also clear how complex such analysis can be. Different applications of servicing are expected to affect these metrics differently.

One clear point from the results for the hypothetical operator is the fleet scheduling. Even though more than 75% of the servicing requests were completed in the planned servicing, the number could be increased with a proper arrangement of when the Client satellites are launched. Considering that in a real commercial case Servicers would be in charge of a larger fleet or multiple fleets, this proves to be necessary. The framework could be used for different iterations to find the balance of fleet metrics, launch time and servicing time.

Additionally, how much refuelling or life extension will be achieved with a servicing operation could be better balanced with the *NPV* of each Client satellite. In this way, any fuel waste or satellite idle time could be avoided.

Regarding the *Current Value*, a simplification considers that this metric does not recover after servicing but only changes its reduction rate (degradation). However, the addition of more fuel or extension of life will clearly bring more value to the Client so this is another metric behaviour to be explored.

For the emergency servicing, the consideration of metrics going to zero after a failure is another point to be refined. The consideration of partial failures could more accurately represent real cases of subsystem failures and servicing.

The simulation of more realistic cases, either from Client or Servicer side, encompasses the metrics presented before but also demands the proper characterisation of each variable (Table 5-1 and Table 6-4) defining the metrics. When one of the primary variables is not provided, the framework uses well-known estimation methods such as cost estimating relationships (CERs) and regression from historic data for satellite parameters. However, considering the limitations and error estimates of such methods, for more representative results the user is expected to provide more refined estimates for such variables.

It should be noted that the context of the simulation will vary, depending on the specific case being considered. Satellite operators have different profiles, demands and concept of operation for their fleets, ranging from technical to commercial/financial aspects. Servicer operators would also be looking at this upcoming market and designing their systems accordingly. Hastings et al. [62] presents a model developed based on behavioural economics which is used to evaluate the long-term effect of servicing in the space industry, bringing results such as trends for servicing cost and trends for servicing adoption. In addition to the current industry/operator needs and interests towards servicing, these results can be used to define variables to explore OOS in the current context and to formulate scenarios to be explored with the framework presented in this chapter.

Additionally, different operators might have specific ways of assessing the value of their satellites. Herein, with focus on the upcoming commercial cases of OOS, *NPV* can be used as main metric for such assessment. However, operators may find value in servicing from the usefulness incorporated to their systems which is not necessarily financially-driven (strategic, scientific or responsive reasons for example). Therefore, the framework also allows the implementation of metrics defined by the user to help it in the tailoring of the simulation for each profile. Such additional metrics can be used in parallel with the metrics presented in this work, not affecting the functioning of the framework. As standard examples found in the literature, *Utility* presented by Saleh et al. [170] is used as a main standard metric for such matter, serving as an overall measurement depending on the user’s concept of operation and requirements.

Due to length limitation, the example presented here considers only the case of *Lifetime Extension*, *Refuel* and *Rescue and Recover* but the methodology can also consider cases such as *Maintenance and Repair (Payload Augmentation)* and even *Re-orbit/De-orbit (Active Debris Removal)*.

6.4.1 Satellite Design and Operation

In this section are discussed some immediate explorations that are possible using the results from the framework presented in the previous sections.

- Extension vs. Refuel: Even though *Lifetime Extension* and *Refuel* have the same final result, the implications in selecting one of them are different. For the former, no major changes in the design of the Client satellite are required as this application relies more on the Servicer side (grappling, berthing and docking mechanisms) [8,16]. Mechanical interfaces already present on the Client satellite such as the interface with the launcher are suitable for this application. On the other hand, the *Refuel* is likely to demand changes in the propulsive systems such as fluidic interfaces, and eventual limitations to the types of fuel. Some of these subsystems were already demonstrated and have a maturity around TRL 7 and 8 [47,171,172]. Despite requiring changes in the Client design, the *Refuel* application allows the Servicer to be more flexible in its operation (multiple Clients) which could reflect in a less costly servicing. The application of *Lifetime Extension*, however, primarily requires the Servicer to be dedicated to one Client at a time, which could lead to a costlier servicing. Another point to be noted regards the chance of the Client operation being affected by the presence of the Servicer, as demonstrated in the example. All the presented metrics are used to explore a suitable option to an operator.
- Mass allocation: The specific mass allocation of the payload and the propulsion subsystem is another design point to take advantage of OOS. The current mass allocated before the satellite commissioning for the propulsion subsystem and fuel is between 50% and 70% of the total launch mass for geostationary satellites. Reducing this mass would allow the operator to add more payload (and auxiliary subsystems such as power) to the satellite, increasing potential revenue. The reduced lifetime could then be balanced by either *Lifetime Extension* or *Refuel* as discussed before. All the metrics discussed in this chapter are the main guidelines to perform such decision-making, in addition to metrics from the operator. This also requires a concurrent evaluation with the Servicer side to guarantee the suitable operation of the Client satellites.

- Flexible payloads: Flexible payloads have been designed to be adaptable to different conditions such as changeable coverage requirements, and target user markets, and are capable of changes during the satellite life. Even though such payloads can keep generating *Income* and *NPV* at (assumed) better conditions than a conventional payload, the satellite is still dependent on the propulsion subsystem to make the most of such a payload. The selection of one of the types of servicing discussed before is an option to reach this, considering the two previous points discussed. For this case, the *NPV* metric has a major role to evaluate this design option.
- Expandable and hosted payloads: Either for the case of a Client operating for its initial design life or for an extended life, the capacity of operating under different conditions such as market changes is one area that can also be explored in the design of a serviceable Client. The addition of extra payloads on demand is one direct option. In this case the electrical-mechanical interface design would have to be revised for a "plug-and-play" payload. Furthermore, the possibility of hosting third party payloads (from smaller operators for example) might allow the operator to extract more income from a satellite, independently from the main mission of the system. For this case, the capabilities of Servicers from *Rescue and Recover* are the main point to explore in the relation of Servicer and Client. Once the new payload is added, the system is expected to change its value and usefulness from the operator point of view so, in addition to *NPV*, specific user defined metrics can be useful in the evaluation of this application. The concept of hosted payload is already used by some satellite operators [29] with plans to use OOS as an enabler for payload incorporation after launch [141].
- Multi-application: The use of a Servicer for multiple servicing applications is another exploration subject of interest. When considering cases with low demand or unpredictable demand, a Servicer could alternate between its tasks, going, for example, from a Client rescue to another Client refuelling or from a Client life extension to the augmentation of the payload of another Client. For this case, observing the periods when the Servicer is idle is relevant to explore the possibility of performing extra tasks. The use of a Servicer with multiple

applications is already anticipated by the upcoming operators such as SpaceLogistics Services [173] and Space Infrastructure Services [169].

6.5 Conclusions

A framework using Agent-Based Modelling Simulation was proposed to relate Client and Servicer sides for different applications of On-Orbit Servicing. A hypothetical satellite operator was used as an example to explore applications of *Lifetime Extension*, *Refuel,* and *Rescue and Recover*. Conditions extracted from real satellite operators and Servicers based on the spacecraft currently in development were used for the demonstration of the framework.

Analysis of OOS with focus on only one side, Client or Servicer, might lead to misguided representation of OOS. Furthermore, considering only individual aspects of a satellite operation, such as DeltaV-only, reliability-only or financial-only can also leave out a portion of the analysis parameters for OOS. The integrated relation of Client and Servicer and the concurrent evaluation of different metrics of the systems, attributes included in the framework, helps to build a more solid analysis of OOS applications in early stages of the design.

7 Use Cases

As discussed in the previous chapters, the interests, expectations and requirements of operators (Client or Servicer) may vary drastically. Having to define those in detail, from an independent perspective and at the current stage of the industry (starting to step-in this area), would demand a specific analysis via interviews, surveys or other sort of questionnaires to understand the OOS from each perspective.

In this chapter, this process is simplified to keep it concise, focusing on how the framework is used to allow this analysis. To do so, four different use cases are outlined based on specific assumptions to define requirements, inputs and other constraints to be used in the framework.

These cases are demonstrations of the use of the framework in relevant scenarios related to OOS. In addition to show the practical use of the framework, the results presented are discussed to demonstrate the potential decisions to be taken regarding servicing.

The cases cover from current services proposed by the industry up to mid-term future opportunities related to servicing which satellite operators have demonstrated interest. In addition to explore the use of the framework, and potential decisions, they serve to illustrate the relation of Servicer and Client operators in a concurrent way for the decision-making process.

7.1 Overall Methodology

The definition of the main cases to be explored is based on the main observed interests currently identified for Servicer and Client operators. They came from points identified through the thesis, Chapter 2 and Chapter 3, as well as from informal discussions and informal interviews with representatives of Servicer and Client sides.

The main interest used herein for the definition of the cases are:

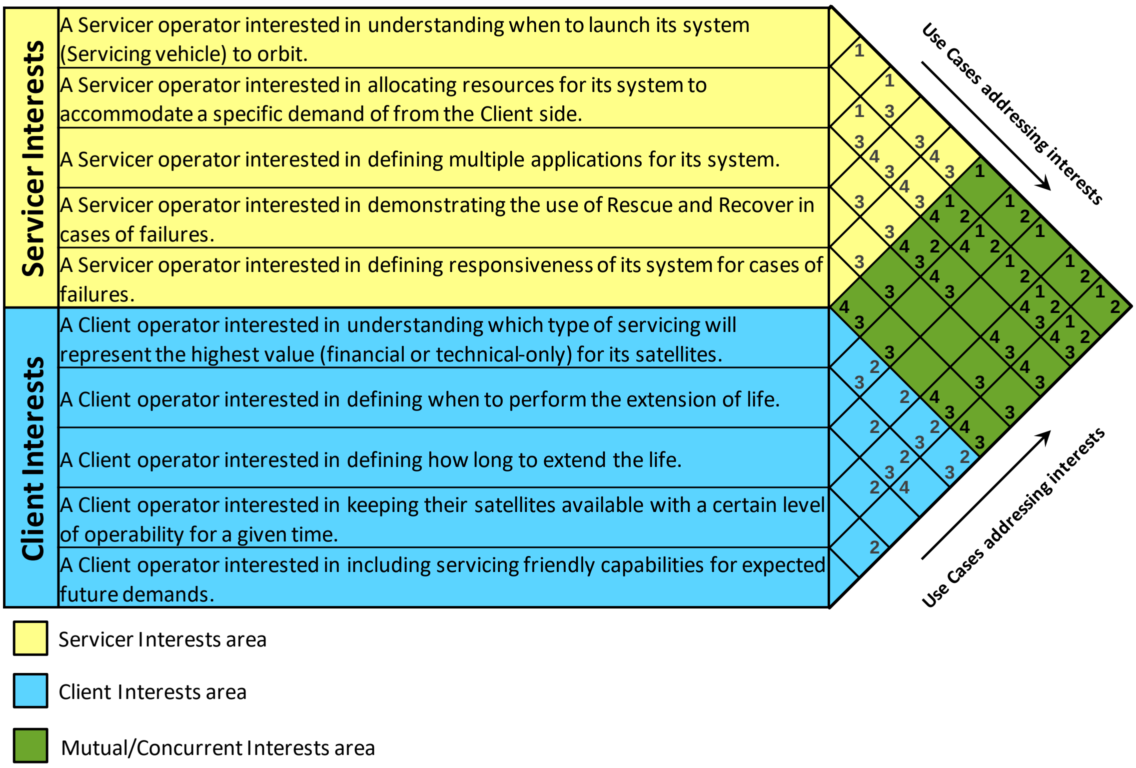
- A Servicer operator interested in understanding when to launch its system (Servicing vehicle) to orbit.

- A Servicer operator interested in allocating resources for its system to accommodate a specific demand of from the Client side.
- A Servicer operator interested in defining multiple applications for its system.
- A Servicer operator interested in demonstrating the use of *Rescue and Recover* in cases of failures.
- A Servicer operator interested in defining responsiveness of its system for cases of failures.
- A Client operator interested in understanding which type of servicing will represent the highest value (financial or technical-only) for its satellites.
- A Client operator interested in defining when to perform the extension of life.
- A Client operator interested in defining how long to extend the life.
- A Client operator interested in keeping their satellites available with a certain level of operability for a given time.
- A Client operator interested in including servicing friendly capabilities for expected future demands.

In addition to the interests presented previously, the main rationales for the proposition of the use cases are the interaction of Servicer and Client operators as well as current and future trends in servicing. A total of four use cases are proposed to explore the presented interests and the use of the framework:

1. *Use case 1: Prospecting for Clients* – Scenario where Servicers are looking for likely potential customers for their services.
2. *Use case 2: Articulating services* – Scenario where Clients are looking for likely potential options or conditions for an offered service.
3. *Use case 3: Multiple Operators and multi-applications* – Scenario where unplanned external Clients may request emergency servicing in an established servicing environment, demanding the Servicer capacity of offering multiple applications.
4. *Use case 4: Servicing mid-term future and persistent platforms* – Scenario where a more established servicing environment is available for operators to choose more advanced servicing applications.

Figure 7-1 illustrates the relation of Servicer and Client interests. This is presented because the proposed cases can encompass multiple interests from both sides. At the intersection of each operators' interests are identified the use case, by its ID number from 1 to 4, in which such relation is presented. The focus herein is on the area where the interests of Client and Servicer are addressed concurrently.



A Servicer operator interested in understanding when to launch its system (Servicing vehicle) to orbit.

A Servicer operator interested in allocating resources for its system to accommodate a specific demand of from the Client side.

A Servicer operator interested in defining multiple applications for its system.

A Servicer operator interested in demonstrating the use of Rescue and Recover in cases of failures.

A Servicer operator interested in defining responsiveness of its system for cases of failures.

A Client operator interested in understanding which type of servicing will represent the highest value (financial or technical-only) for its satellites.

A Client operator interested in defining when to perform the extension of life.

A Client operator interested in defining how long to extend the life.

A Client operator interested in keeping their satellites available with a certain level of operability for a given time.

A Client operator interested in including servicing friendly capabilities for expected future demands.

🟨 Servicer Interests area

🟦 Client Interests area

🟩 Mutual/Concurrent Interests area

Figure 7-1 – Interests Relation – Use Cases demonstration of Client and Servicer interests

It is important to note that, even if the interests presented in the table do not correlate, the user can still use the framework to explore OOS from its individual perspective. The approach used herein is intended to optimise the demonstration of the framework's capabilities and how it fills the observed gap in this area.

Each use case is presented in a standardised form, indicating the main inputs used in the analysis, as well as a summarised methodology used to achieve the results presented. This summarised methodology comprises of specific steps the user would take using the framework during the analysis based on the main objectives coming from Client and

Servicer interests. Table 7-1 presents the relation of the use cases and the framework capabilities discussed in Chapter 3 and Chapter 5.

The proposed use cases provide the means to demonstrate all the key capabilities (Chapter 3 and Chapter 5) of the tool as well as how they meet the objectives defined for this thesis (Chapter 1).

Table 7-1 – Use Cases and framework capabilities demonstration

Tool Capabilities	Case 1	Case 2	Case 3	Case 4
Analyse satellite servicing plans and operation scheduling to understand how the launch time and the expected servicing will affect the fleet operation.	X	X	X	X
Analyse the system overall degradation to understand which type of servicing fits better for the satellites of an operator fleet.	-	X	X	X
Simulate eventual failures and analyse the overall fleet response with and without servicing.	-	-	X	-
Perform initial trade-offs and design of required systems to accommodate different types of servicing.	X	X	-	X
Concurrent elaboration and refinement of Client requirements and Servicer capabilities.	-	X	-	X
Analyse the cost-benefit of servicing compared to a “classical” fleet management approach.	X	X	X	X

The satellite samples used for this chapter are presented in Appendix H with an overall summary presented in Table 7-2. SpaceTrak [168] is the main database used to identify potential Client satellites as well as the characteristics/information necessary for the simulation in the framework. Considering that this database can still present incomplete data/information about these assets, an initial filter is applied to censor/remove satellites without enough information that could not be estimated using any of the methods discussed in the previous chapters (CER’s, historic data, mass budgets, etc). This step would be unlikely to happen in a real-case scenario since both parties would have a comprehensive knowledge of the systems they would want to simulate and analyse.

The samples used in this chapter are also subdivided in smaller populations in each case when necessary. The subdivision in smaller populations is to allow a clearer representation of the results, since the output handling routines of the framework are currently limited[12] to 256 Client satellites. The division in smaller populations also allows the grouping of satellites within giving date ranges, from the past to current commissioned satellites. Table 7-2 shows a brief description of all the samples and populations (if applicable).

Table 7-2 – Summary of Samples and Populations

	Sample 1	Sample 2	Sample 3
Number of satellites	549	6	15
Number of populations	3	1	1
Clients per population	183	6	15
SpaceTrak Date Range [a]	From 01/01/1990 To 10/09/2018	From 14/11/2010 To 04/05/2017	From 04/12/2018 To 15/08/2025
Main characteristic	Past/current operational satellites	Satellites with anomalies	Future operational satellites
Applicable to Use Case	1, 2 and 3	3	4

[a] For Sample 1, the date ranges for each population are the following:

- Population 1: From 01/01/1990 to 14/09/2000
- Population 2: From 01/10/2000 to 14/10/2010
- Population 3: From 28/10/2010 to 10/09/2018

The detailed parameters used for each Client Sample and for the different Servicers are presented respectively in Appendix H and Appendix J. The parameters provided in both appendices are in the direct format to be inputted in the framework for the simulation. The total running time for each simulation are presented in the summary of each case as well as in the Appendix G.

7.2 Cases

The four use cases described previously are explored in detail in the following subsections. Each subsection is presented with a brief description of the parameters, the methodology used, and the results and discussion for the use case.

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[12] Limited by the current number of series Excel can handle in a single chart. This limitation is discussed in the next chapter.

7.2.1 Use case 1 – Prospecting for Clients

This case examines the scenario where Servicers are looking for likely potential customers for their services.

The case is of main interest of the Servicer side as it explores the market potential of a proposed servicing system. Based on the main concept of operation of a specific Servicer, the servicing of a number of Clients can be simulated using the framework, assessing the potential benefits for the Servicer side. The results could then be used by the Servicer operator to start the discussion with potential Clients, highlighting on the advantages of servicing using that specific Servicer.

7.2.1.1 Parameters

The assumption of parameters is based on the current servicing options available commercially [45,50,54–57]. The main characteristics of offered extension and servicing time are used to define the initial conditions described as follows. Being based on a commercial case, the *NPV* filter is aimed to provide profit to the Servicer. The Client populations are used as described in Table 7-2.

- **Applications considered**
    - *Lifetime Extension*, and *Maintenance and Repair* (Refuel)
- **Rationale**
    - Current commercial endeavours to make OOS a viable/applicable solution, therefore focused on Servicer operators providing solutions to GEO satellites.
- **Population simulated**
    - Sample 1 subdivided in three main populations, classified by launch date (Table 7-2).
- **Assumed inputs and constraints**
    - *Pre-assignment of OOS applications*: Clients to *Lifetime Extension*.
    - *Minimum advantage/profit for selecting/opting for servicing solutions*: >0% *NPV*

- *Initial Servicer intended profit*: 10% (based on spent resources)
- *Initial servicing trigger*: 70% and 50% life (MR and LE respectively)
- *Initial extension of life*: 30% and 20% of design life (MR and LE respectively)
- *Servicer operational constraints*: Starting operation at the Client position and time of the first servicing mission, unconstrained replenishment of resources (if applicable), non-extendable life, single application.

7.2.1.2 Methodology/Steps

This use case explores the use of the framework from the perspective of the Servicer operator based on the following steps:

1. First run using parameters presented in the previous section;
2. Client censoring/filtering based on minimum profit defined, starting with *Lifetime Extension* application;
3. Iteration until all serviced Clients meet the requirements (Minimum *NPV*);
4. Adjustments of Servicer resources usage to define a suitable sizing for the following parameter: *operational life* (t_{Life}), *resources to sell* ($m_{prop\text{-}sell}$ *Refuelling* cases), expected mass of Client (*Lifetime Extension* cases) and *profit*;
5. Client censoring/filtering based on minimum profit defined for *Maintenance and Repair* (Refuel) application;
6. Iteration until all serviced Clients meet the requirements (including raising the minimum profit requirement);
7. Adjustments of Servicer resources usage to define a more suitable sizing for the following parameter: *operational life* (t_{Life}), *resources to sell* ($m_{prop\text{-}sell}$ *Refuelling* cases), expected mass of Client (*Lifetime Extension* cases) and *profit*;
8. Final run.

The assignment of a given servicing application to a Client satellite is a necessary step for this use case. However, as the case is focused on the Servicer prospecting potential Clients, the first assignment of these applications, in this case, is up to the Servicer side.

As it will be presented in detail and discussed later, the outcomes of the simulation can vary considerably whether using *Lifetime Extension* or *Refuelling* concepts.

Since the Servicer in this case would still want to offer an attractive option to potential Clients, the assignment of servicing application to the Client satellites is made based on a filtering process. This filtering process focuses on providing a minimum of *NPV* advantage/improvement when extending the life of a Client. Therefore, first are filtered Clients capable of achieving financial benefits (*NPV*) using a *Lifetime Extension* Servicer. The Clients filtered out of the first selection are then assigned with *Maintenance and Repair* (Refuelling) for another round of selection. At the end, the Servicer operator is left only with Clients capable of achieving financial benefits (*NPV*) using the proposed servicing solutions.

Figure 7-2 shows the overall flowchart for the simulation and filtering steps described previously.

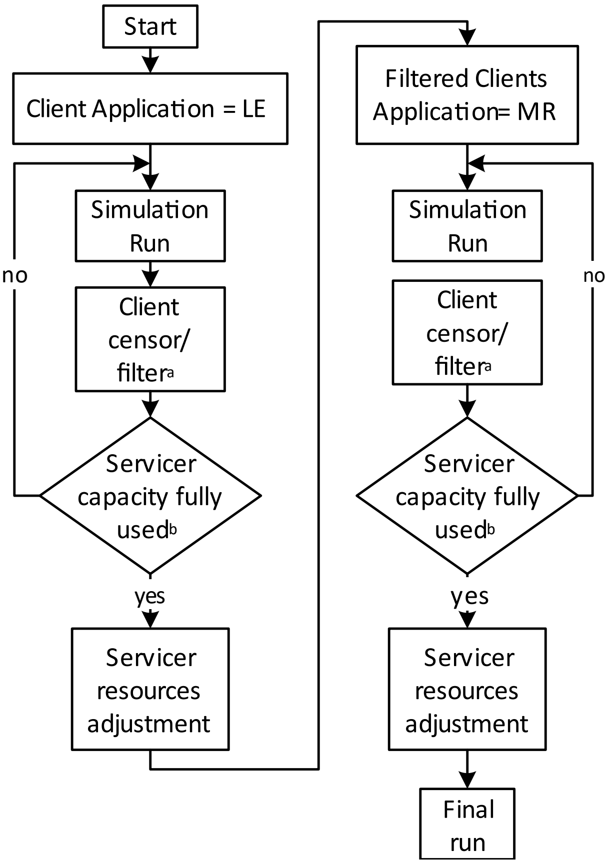


Figure 7-2 – Simulation and filtering flowchart

[a] Censoring/filtering of Clients is based on the criteria defined, herein minimum *NPV*. Filtered Clients have the application changed to "*None*". This remains until the next application check, when filtered Clients are assigned for "*Maintenance and Repair*" for another round of filtering.

[b] The check and loop steps are necessary to allow the simulation to run another time when a Client is filtered in the current run. Running the simulation consecutive times allows the consideration of a potential Client not serviced in the current run. Such a Client could then be accommodated in the Servicer available time left from the previous iteration. This check is driven from a Servicer perspective to consider all the possible Clients for its available resources and operational life. Resources not used are adjusted in step 4 and step 7, allowing the Servicer to be suited for that given group of Clients to be serviced.

7.2.1.3 Results and Discussion

This approach would be likely to be used by Servicer operators prospecting for potential Clients/markets to offer their services, while sizing their systems and constraints. It provides an overall picture which is likely to be attractive for both cases (Client and

Servicer), in a context of competing services, assuming these would be provided by different operators.

The results for the three different populations are presented from Figure 7-3 to Figure 7-11. The dashboards provided are part of the output generated by the framework, summarizing the major information the user would analyse when exploring servicing cases. The main metrics described in Chapter 5 are presented for Client and Servicer and additional information about the operation and simulation summary are also presented in the dashboard.

The individual timelines for each Client are not provided herein due to space limitation. These, however, are used in the analysis process between steps 3 and 6, checking for periods when the Client waits for servicing for a long time. In case a Client is left waiting for a servicing operation for too long, changes in the operation or servicing conditions to reduce the waiting time can be made.

The dashboards generated by the framework are presented by parts for a better readability. The complete dashboards as generated by the framework are presented in the Appendix.

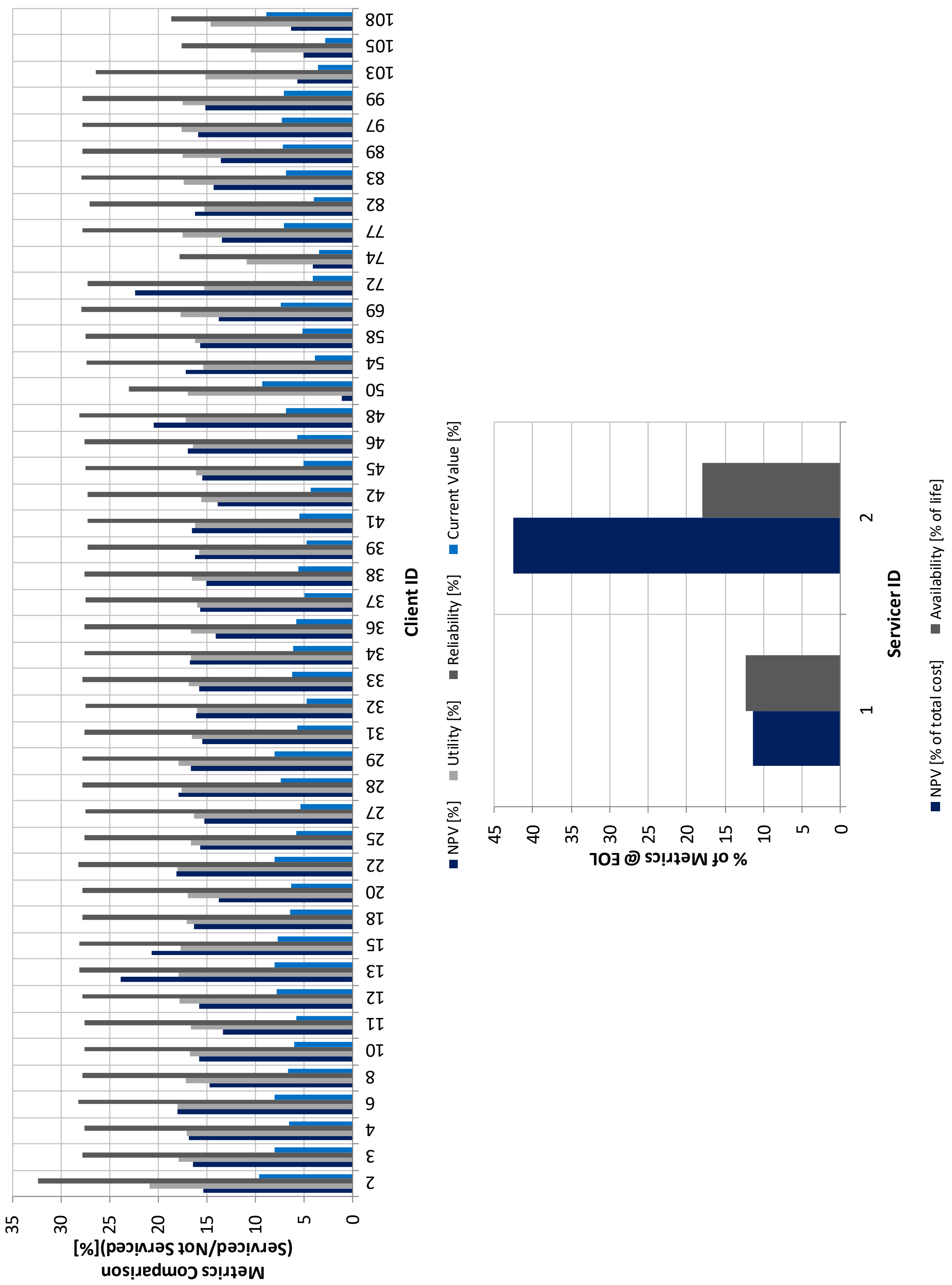


Figure 7-3 – Simulation Dashboard – Population 1 (Part 1 of 3) – Comparison / Trade-offs

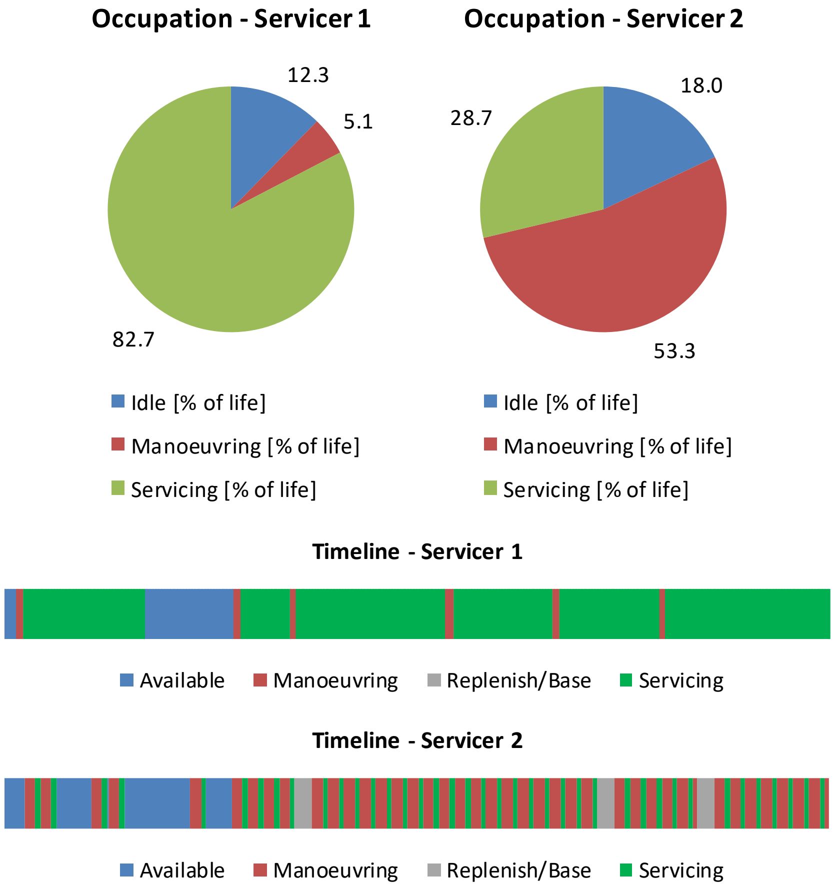
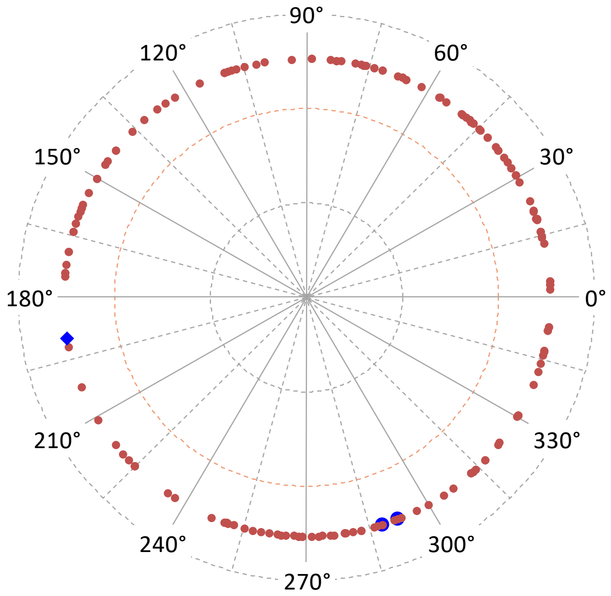


Figure 7-4 – Simulation Dashboard – Population 1 (Part 2 of 3) – Workload and scheduling



Lifetime Extension	
Tickets Open	7
Tickets Assigned	7
Tickets Completed	6
Average Waiting Time [years]	2.208219
Average Manoeuvre ΔV [km/s]	0.065503
Average Propellant Mass [kg]	21.41859

Maintenance and Repair	
Tickets Open	157
Tickets Assigned	41
Tickets Completed	40
Average Waiting Time [years]	0.746542
Average Manoeuvre ΔV [km/s]	0.034276
Average Propellant Mass [kg]	51.12896

Figure 7-5 – Simulation Dashboard – Population 1 (Part 3 of 3) – Location, resources and time

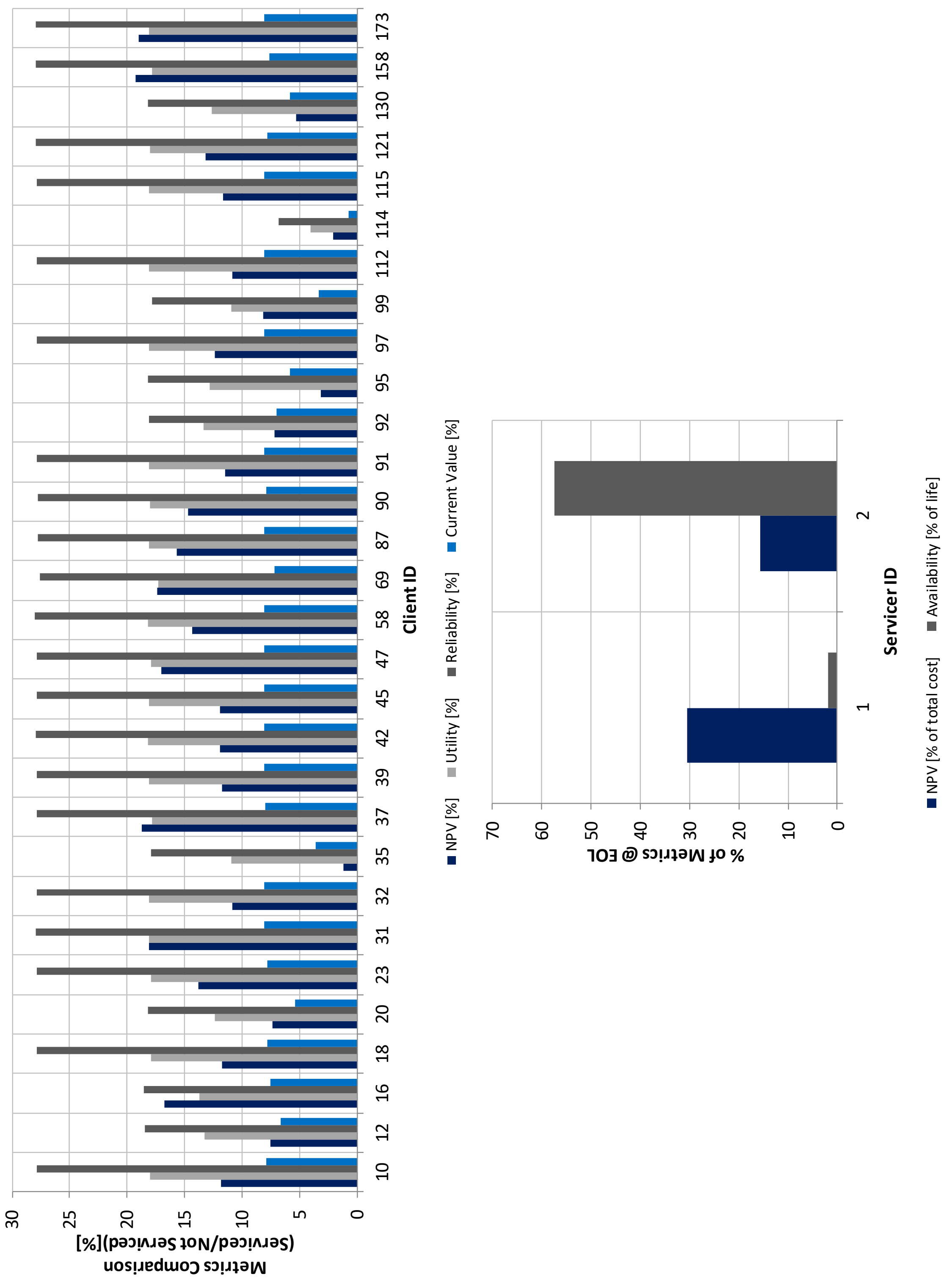


Figure 7-6 – Simulation Dashboard – Population 2 (Part 1 of 3) – Comparison / Trade-offs

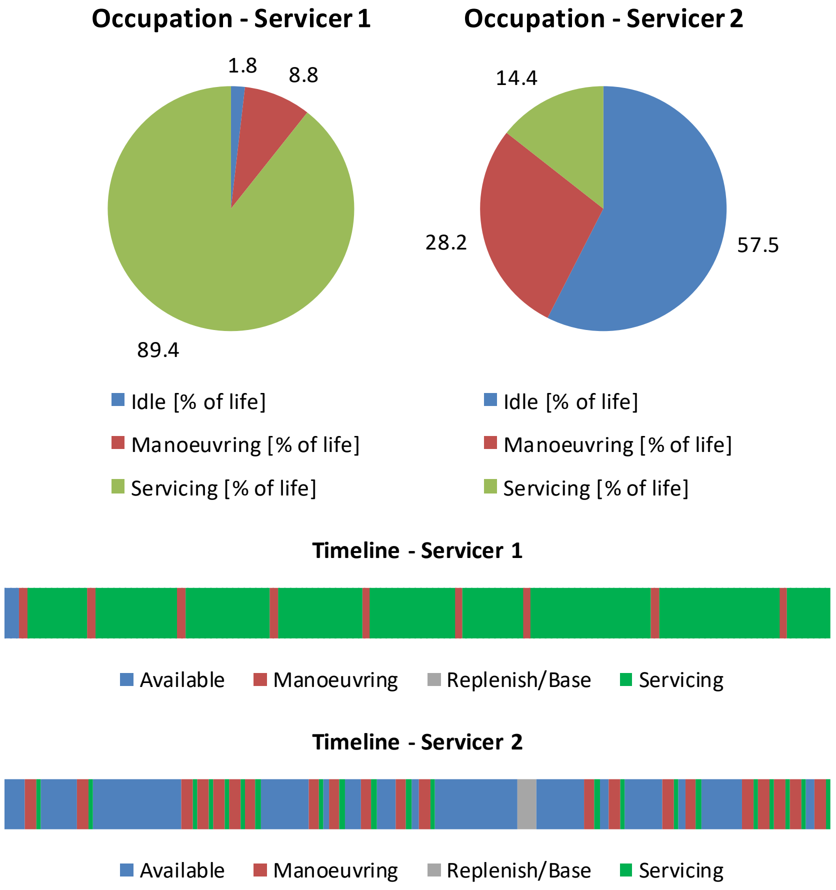
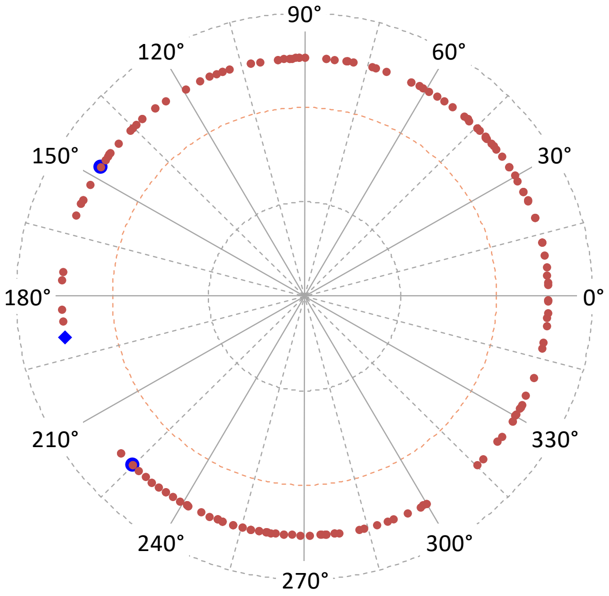


Figure 7-7 – Simulation Dashboard – Population 2 (Part 2 of 3) – Workload and scheduling



Lifetime Extension	
Tickets Open	9
Tickets Assigned	9
Tickets Completed	9
Average Waiting Time [years]	1.527854
Average Manoeuvre ΔV [km/s]	0.073405
Average Propellant Mass [kg]	15.72892

Maintenance and Repair	
Tickets Open	95
Tickets Assigned	21
Tickets Completed	21
Average Waiting Time [years]	0.052968
Average Manoeuvre ΔV [km/s]	0.025164
Average Propellant Mass [kg]	89.52999

Figure 7-8 – Simulation Dashboard – Population 2 (Part 3 of 3) – Location, resources and time

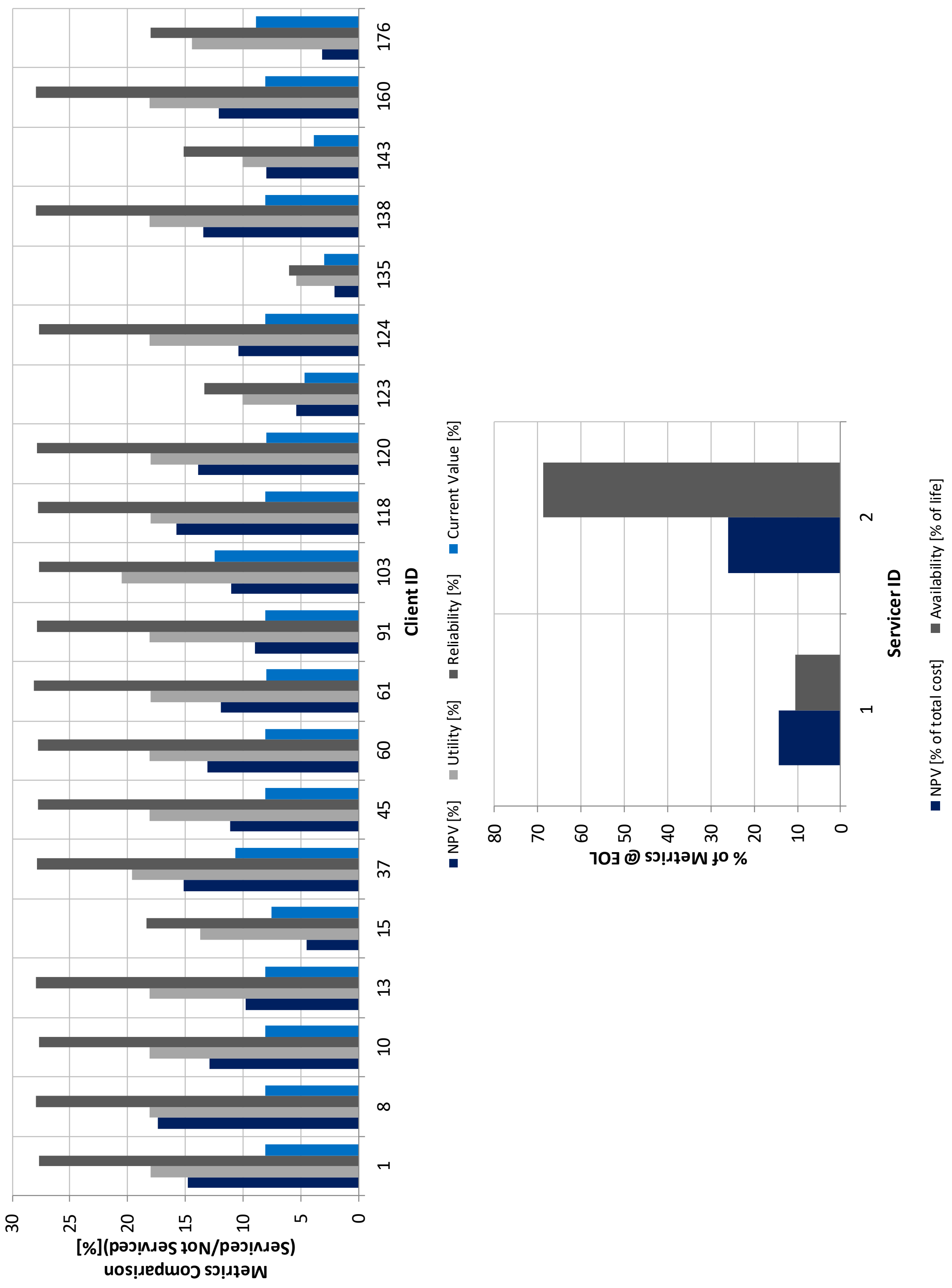


Figure 7-9 – Simulation Dashboard – Population 3 (Part 1 of 3) – Comparison / Trade-offs

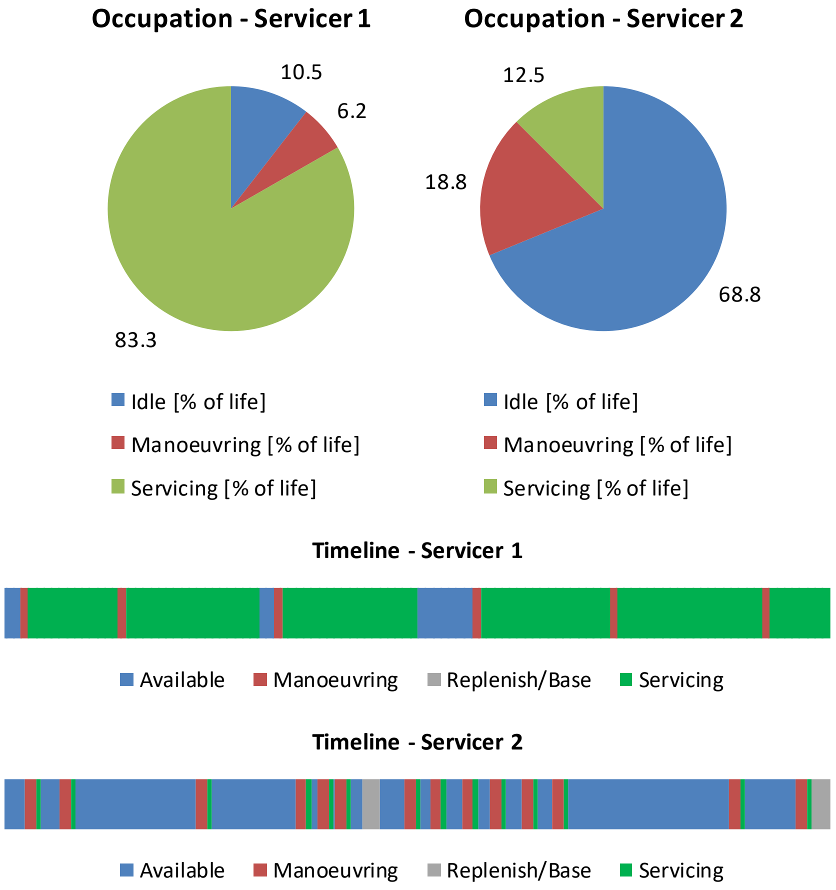
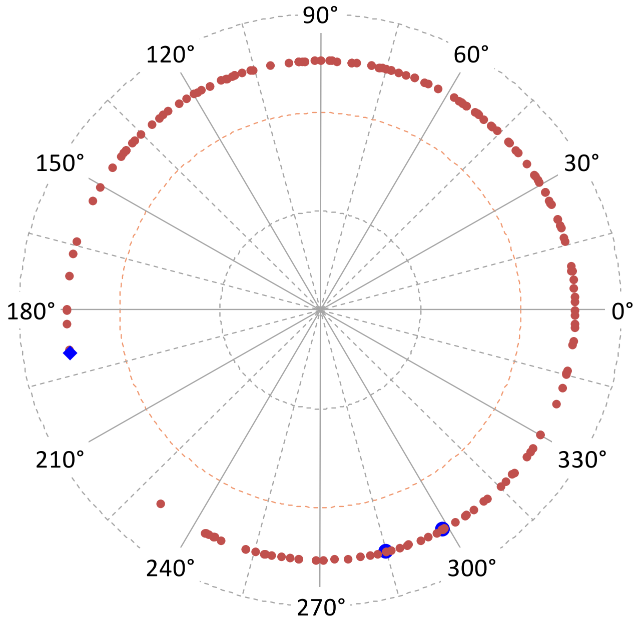


Figure 7-10 – Simulation Dashboard – Population 3 (Part 2 of 3) – Workload and scheduling



Lifetime Extension	
Tickets Open	6
Tickets Assigned	6
Tickets Completed	6
Average Waiting Time [years]	0.674429
Average Manoeuvre ΔV [km/s]	0.11907
Average Propellant Mass [kg]	22.11137

Maintenance and Repair	
Tickets Open	54
Tickets Assigned	14
Tickets Completed	14
Average Waiting Time [years]	0
Average Manoeuvre ΔV [km/s]	0.028313
Average Propellant Mass [kg]	107.3442

Figure 7-11 – Simulation Dashboard – Population 3 (Part 3 of 3) – Location, resources and time

Table 7-3 presents a summary of characteristics and results from each population of the current case.

Table 7-3 – Simulation Summary – Sample 1 (Population 1 to Population 3)

	Population 1	Population 2	Population 3
Simulation Time	30 years	30 years	30 years
Clients Simulated	183	183	183
Clients Serviced	46	30	20
Total life extended [a]	109.40 years	78.52 years	55.67 years
Client *NPV* Filtering Target (MR)	10%	5%	5%
Client *NPV* Filtering Target (LE)	0%	0%	0%
Client Average *NPV* (MR) [b]	16.28%	14.17%	12.41%
Client Average *NPV* (LE) [b]	6.27%	6.53%	6.89%
Replenishments (Servicer MR)	3 times	1 time	1 time [c]
Spent Resources [d] (Servicer)	2173.67 kg	2021.69 kg	1635.49 kg
Simulation Running Time	108 seconds	113 seconds	116 seconds

[a] Total useful life extended for all the Client satellites using both refuelling and tugging methods.

[b] Calculated based only on the serviced Clients.

[c] Although the Servicer was replenished twice, the resources of the second replenishment operation were not used in any servicing operation.

[d] Resources used for manoeuvres and refuelling (if applicable).

The method used for this case allows the exploration of a given Client population by one or multiple Servicer providers operating in a competitive environment. While Clients more suited for *Lifetime Extension* are selected first, those are less numerous when compared to those best suited for Refuelling, due to the limitations of the Servicer in addressing many *Lifetime Extension* Clients in its design life. The remaining Clients are then explored again for *Refuelling* until the Servicer capacity is fully used.

The Clients left without any servicing application assigned after the filtering are equally useful for the analysis, helping to understand why is servicing not beneficial for some Clients. Among factors potentially leading to a not beneficial servicing could be highlighted, for example, timing/scheduling servicing was expected, cost and value of Client and charged servicing and resources available. This could be used to indicate upfront any trends or parameters for the satellites with a non-attractive condition for servicing. For this latter case, a more in-depth analysis could be performed using the framework to explore any correlation of Client and Servicer initial conditions and the final outputs.

Even though the approach may require a more particular analysis of the Clients after the first filtering, this is a capability provided by the framework which is not observed elsewhere. Environments such as Concurrent Design meetings are particularly relevant to this step, in which both sides could be discussing about how to define the simulation and system parameters.

A point to be noted about the filtering method used herein is that it can represent a more aggressive filtering of potential Clients. Considering the concurrency of all the agents (Clients and Servicers), the presence or absence of a Client can directly affect the servicing and operation of other Clients. Censoring/removing a large batch of Clients can represent a more drastic impact in the operation of the remaining Clients of the filtered population. Among the potential impacts, those related to the scheduling of servicing are the most evident. The same method could be used in a more incremental and conservative approach, removing/filtering only Clients with the worst result for a given parameter (e.g. *NPV*), then simulating again for the new fleet condition. This would allow a more incremental view of how the entire fleet and simulation conditions evolve, however, this process can be considerably time-consuming. This also highlights how the same conditions could lead to different acceptable solutions, compatible with Client and Servicer requirements.

Additionally, using the framework with this methodology helps to define more realistic options for servicing in a context where not enough information might be available. As it can be noticed by the results (also discussed previously Chapter 5), *Refuelling* cases will have more flexibility due to the availability of the Servicers (shorter servicing times) and Client demands. However, in order to consider a more conservative view of a given population demanding servicing, the filters help to define a more balanced trade between Client and Servicer metrics, *NPV*-based in this use case. Also, for *Lifetime Extension*, it allows the selection of the most suitable Clients for the same balance.

Since this case does not classify the Client satellites based on the constellation or operator they might belong to, the analysis of the scheduling of servicing, from the Client perspective, is limited. It would be necessary to define more constraints of how flexible or keen the operator would be in delaying or anticipating the commissioning of a satellite. From the Client side, the decision of allowing a servicing task to occur earlier or later would be influenced by the Servicer operator which would be looking to avoid longer periods in Idle state.

This case demonstrates that the cases of extension of life by the two different methods can represent a potential eco-system for servicing. While *Lifetime Extension* providers can focus on specific Clients likely to get profit from this application, *Refuelling* providers could have more flexibility in planning the logistics of operation and resources management for operations with Clients to be refuelled.

The approach of censoring/filtering satellites which are not attractive based on the conditions pre-defined for Client and Servicer are still useful for the Client, even though this approach would be employed by a Servicer operator. In a case of a Client operator with a large fleet, this filtering process can allow the understanding of an appropriate scheduling based on the differences of the launch date for each Client satellite. In this way the user is left with the decision of either contracting a different servicing option for those Clients left out/filtered or re-arranging the scheduling of the fleet itself.

After the filtering/censoring, if the Servicer has idle periods, this could be reduced with an individual look at the Client being serviced prior to or after the idle state. Clients prior to the idle state could continue calling for servicing at the same time, but for a longer extension of life, fulfilling part of the Servicer idle period. Also, the same preceding Clients could have the originally contracted extension of life, but in a later time of the life. As a last option, Clients addressed after the Servicer idle period could be serviced earlier.

Using the framework for fine tuning of the parameters of such a Client (prior to or after the idle time) could improve the usability of the Servicer, reducing idle conditions. This would necessarily need to represent an attractive option for the Client, either due to an improvement in the output at the end of life (e.g. *NPV* or *Utility*), or conditions offered by the Servicer itself (e.g. potential costs deduction). The outputs provided by the framework, mainly represented in the dashboard, are valuable information to be used in such a discussion. In this way, the framework guides the user to the most appropriate interval to be targeted between servicing operations, avoiding planning consecutive operations that will not likely occur due to non-availability of the Servicer or non-agreement of the Client.

Although more Clients serviced would have the tendency of representing more profits from the Servicer side, this is not valid all the times. Having fewer Clients could represent a more tailored service provided and less waiting time from the Client side. One observed behaviour is that, for *Lifetime Extension*, the later the servicing occurs, the higher the chances will be of a non-attractive outcome. The framework does not use a specific decision routine to verify if it would still be appropriate to service a Client after it has spent a long time in Scheduled state. Due to a long wait the Client could be very close to the end of life, not justifying any servicing depending on the behaviour of its financial variables (how flat *NPV* gets towards the end of life as function of decaying *Utility*). Such an attribute is capable of being implemented in the framework via a simplified condition check, but this would represent another parameter to be defined by the users.

The framework allowed to understand how *Lifetime Extension* can be a very sensitive case to provide an attractive option while still getting benefits in offering it. It indicates as well that more work needs to be implemented in the exploration of how agents charge each other and the calculation of servicing prices.

This process still does not guarantee an overall optimum case for the fleet. The satellites removed in one batch of the filtering/censoring could have potential to achieve a better condition in a later run. However, it becomes challenging to estimate if this would be the case or not due to the concurrency of the Client satellites of the fleet. This approach will ultimately show the best conditions a given Servicer can provide considering a specific demand from the Client fleet. One way of bypassing this would be the definition of priority Clients for which the user wishes to explore a given type of servicing, and deciding which agents should be filtered/censored first or later.

7.2.2 Use case 2 – Articulating services

This case examines the scenario where Clients are looking for likely potential options or conditions for an offered service. The case is of main interest of the Client side as it explores how proposed services could improve (financially for this case) the operation of the fleet. Using as a starting point the standard options offered by a Servicer operator, the Client operator uses the framework to explore attractive conditions for its fleet. Such conditions could then be used to engage the discussion/negotiation with the Servicer side over potentially attractive servicing conditions identified. Ultimately, the use case shows the framework allowing a more direct cooperation between Client and Servicer.

7.2.2.1 Parameters

The assumption of parameters follows the same rationale from Use Case 1, based on the current servicing options available commercially [45,50,54–57]. The Client population is part of the full Population 3 used previously. In this case are used only the serviced Clients from the previous use case. The offered extension and servicing time are defined using the Solution Exploration feature following the method illustrated in Figure 7-12. The same conditions for the Servicer operation, i.e. resources and launch time are used from the previous case. As the servicing conditions are defined using the Solution Exploration, the intended Servicer profit can be adjusted to keep it in a commercially viable condition.

- **Applications considered**
  - *Lifetime Extension,* and *Maintenance and Repair* (Refuel)
- **Rationale**
  - Current commercial trends towards OOS, leading the GEO operators (mid to large fleets) to explore current options for their individual case.
- **Population simulated**
  - Clients filtered from Case 1 (Sample 1 – Population 3).
- **Assumed inputs and constraints**
  - *Pre-assignment of OOS applications*: As defined in Case 1

- *Initial Servicer intended profit*: As defined in Case 1 and iterated with Client side.
- *Initial servicing trigger*: Extracted from Solution Exploration and iterated to improve fleet *NPV*.
- *Initial extension of life*: Extracted from Solution Exploration and iterated to improve fleet *NPV*.
- *Servicer operational constraints*: Starting/launched at the time of the first servicing mission, unconstrained replenishment of resources (if applicable), non-extendable life, single application.
- *Client operational constraints*: Based on limitations imposed by other Clients of the fleet.

7.2.2.2 Methodology/Steps

This use-case explores the use of the framework from the perspective of the Client operator, approached by the servicing provided from Case 1, using the following steps:

1. Solution Exploration for each application (*Lifetime Extension* and *Maintenance and Repair* – Refuel) starting from the parameters proposed (life extension and servicing point) by the Servicer;
2. Identification of the average for the metrics of interest (*NPV* herein) and conditions leading to a suggested optimum;
3. Iteration of life extension and servicing point using as references values suggested by the Servicer operator and values suggested by the Solution Exploration;
4. Final run.

The flowchart in Figure 7-12 illustrates the steps described previously. The process illustrated in Figure 7-12 is used for *Lifetime Extension* and *Maintenance and Repair*. The information presented in blue are the parameters adjusted by the Client operator (*Client Life Extension* and *Servicing Trigger Point*). This adjustment uses as boundaries the results for the Solution Exploration and the parameters defined by the Servicer operator (from Use Case 1). The information coming from Use Case 1 is represented by the dashed lines.

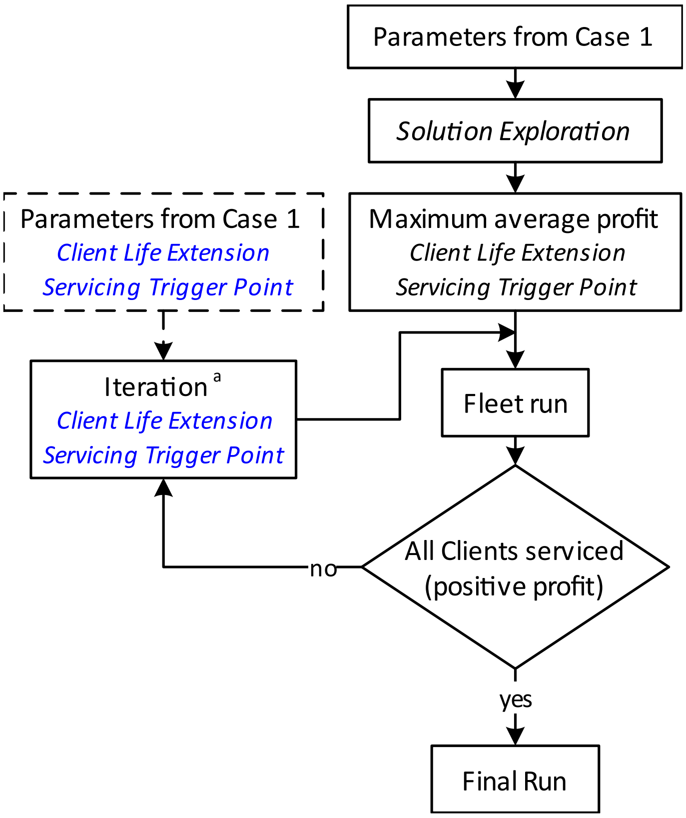


Figure 7-12 – Flowchart (Use Case 2) – Solution Exploration and definition of servicing parameters

[a] The iteration is made for each Client satellite of the fleet until all are serviced with positive profit.

7.2.2.3 Results and Discussion

From the Clients presented in Case 1, in which a viable option to OOS was defined for both Client and Servicer, Population 3 from the sample is used. For simplicity, it is assumed that this sub-sample comprises of Client satellites of a specific fleet from a single operator. Population 3 is selected due to its simplicity from an operational point of view. While the other two populations presented higher potential from financial perspectives, the selected population fits within the servicing operations expected for the next five years (described in Chapter 2), with a more simplified operation and limited scope of Clients.

This case would likely be the following step after a Servicer operator showcases its capabilities and options, attracting the Client operator attention. In this way, the Client operator uses the framework to explore other possible conditions for its fleet, based on the services provided by that given Servicer.

The Solution Exploration feature of the framework (Chapter 5 section 5.3.3) is used to explore the fleet optimal condition, based on a single Servicer. The conditions for life extension and time of servicing leading to the most attractive outcome for the Client are then considered for the entire fleet. Adjustments are made for cases where the servicing of a Client interfere with another Client. These adjustments are related to the points discussed in the previous use case, in the parameters defining the amount of life extended and the time of servicing.

Still, the options provided by the solution exploration can have different effects on each Client, and over the complete fleet. Therefore, comparing the outputs for the standard initial parameters and the parameters suggested by the solution exploration is an important step to consider satellites individually.

Table 7-4 presents the main parameters used for the solution exploration.

Table 7-4 – Solution Exploration Parameters – Use Case 2

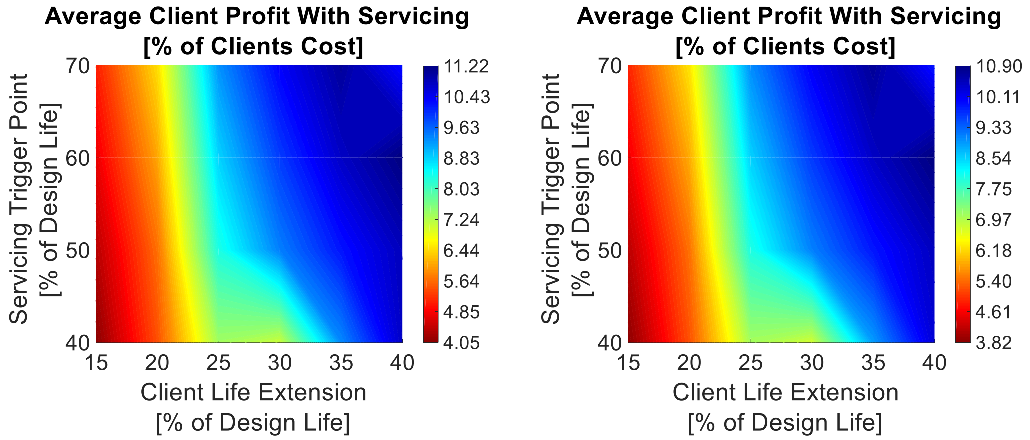
Parameter	*Maintenance and Repair*			*Lifetime Extension*		
	Min.	Max.	Step	Min.	Max.	Step
Servicer Cost Ratio	100% [a]	100% [a]	5% [b]	100% [a]	100% [a]	5% [b]
Servicer Profit	40%	55%	5%	80%	95%	5%
Client Life Extension	30%	60%	5%	15%	40%	5%
Servicing Trigger Point	50%	80%	10%	40%	70%	10%
Average Client Cost	292 M$*			172 M$*		

[a] *Servicer Cost Ratio* is constrained in both cases to keep the analysis with the specific Servicer cost from Case 1.

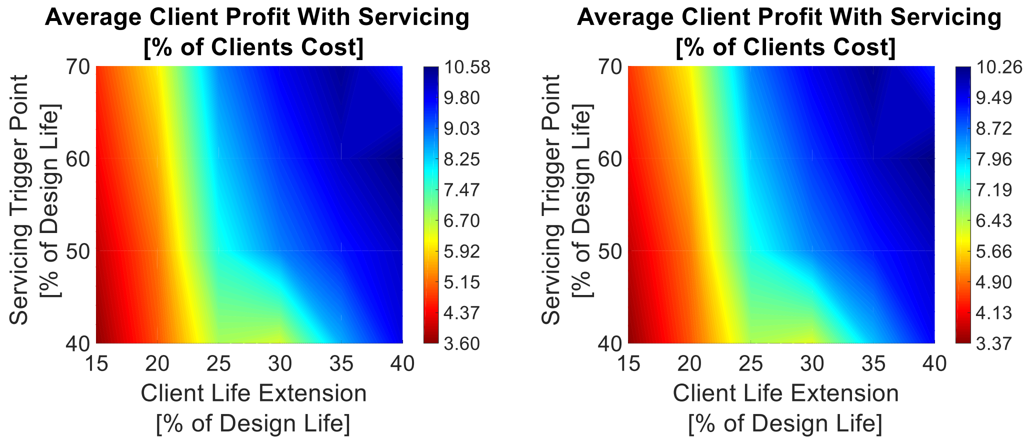
[b] The current version of the framework only allows non-zero values to be used *Servicer Cost Ratio* step input. The Δ between maximum and minimum values is divvied by the step value to calculate the number of simulations for a given input. The values for minimum and maximum are kept 100% with a step of 5% as a simplified way to allow the tool to operate properly.

Figure 7-13 and Figure 7-14 present the results for the exploration from a Client perspective (*NPV* focused), for different expected profits for the Servicer. Since this case focuses on the Client side and the Servicer profit was analysed in Case 1, the comparison of Client and Servicer *NPV*’s is not the main objective herein. The complete output with all the metrics is presented in Appendix H.

The values shown in Figure 7-13 and Figure 7-14 indicate the additional Client profit above that achieved in a complete life without servicing. As described in Chapter 5, the profit of a satellite at the end-of-life is used to compare with the profit at the end of the serviced life. For example, a profit at the end of the serviced life of 0% indicates that a satellite achieved the same profit of the normal life, not necessarily representing an unattractive option from the Client operator perspective.



(a) 80% Servicer intended profit (b) 85% Servicer intended profit



(c) 90% Servicer intended profit (d) 95% Servicer intended profit

Figure 7-13 – Solution Exploration Results – Lifetime Extension (Additional profit above that achieved without servicing) [13]

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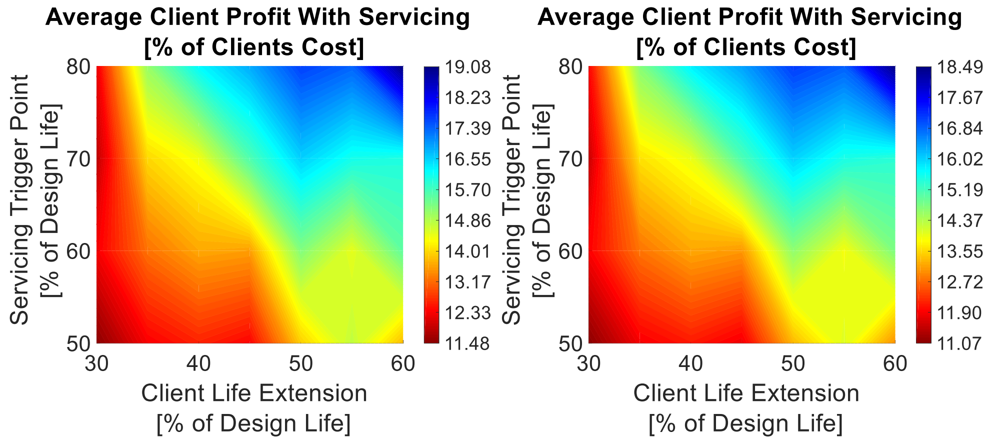
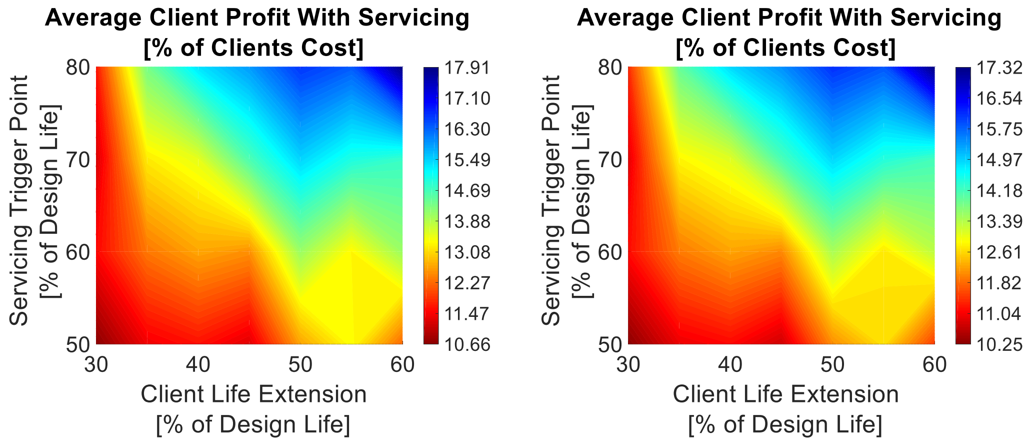
[13] The Client profit indicated in the charts represents the additional profit above that achieved over a life without servicing. The results are presented in percentage of the Client satellite total cost (C_0).



(a) 40% Servicer intended profit (b) 45% Servicer intended profit



(c) 50% Servicer intended profit (d) 55% Servicer intended profit

Figure 7-14 – Solution Exploration Results– Maintenance and Repair (Additional profit above that achieved without servicing) [13]

The solution exploration feature could be used for each Client satellite at a time, however this "removes" the satellite from the context of interaction with other Clients satellites and the availability of the Servicer. The approach used herein acts as a bridge between having generalised parameters (coming from Case 1 for extension of life and servicing time) and those coming from the solution exploration (average of the entire fleet). Still, this feature, in its individual form or combined with external information as presented in this case, is not observed to be available in any other ongoing research, highlighting the capability of the framework.

From the results, the timelines of the Clients are presented, which could be used to discuss whether the Servicer would be available/responsive at a given requested time. From the entire fleet, normally Clients assigned to *Lifetime Extension* would spend a longer time in the Scheduled state due to the Servicer operation with other Clients. From the timelines in Figure 7-15, Client 6 and Client 14 can be identified as cases where the operator would be looking to improve the servicing responsiveness, potentially improving the profit and *NPV* at EOL. This then could be articulated between both operators, leading the Client side to decide for a better servicing condition for its fleet or even a different launch date. The dashboard for this use case is presented from Figure 7-16 to Figure 7-18.

Figure 7-15 – Client Timelines – Fleet (Population 3) – Workload and scheduling

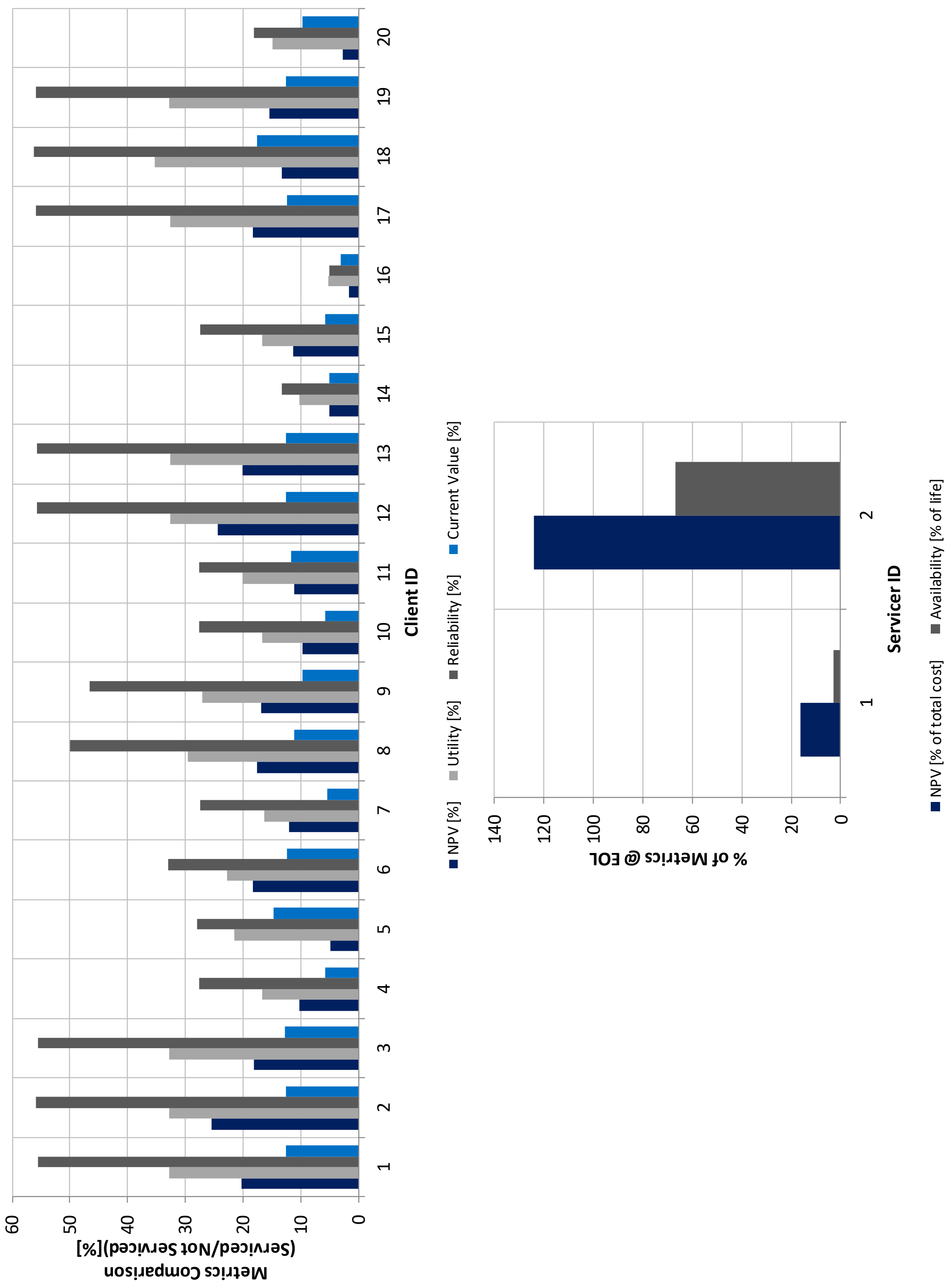


Figure 7-16 – Simulation Dashboard – Population 3 (Part 1 of 3) – Comparison / Trade-offs

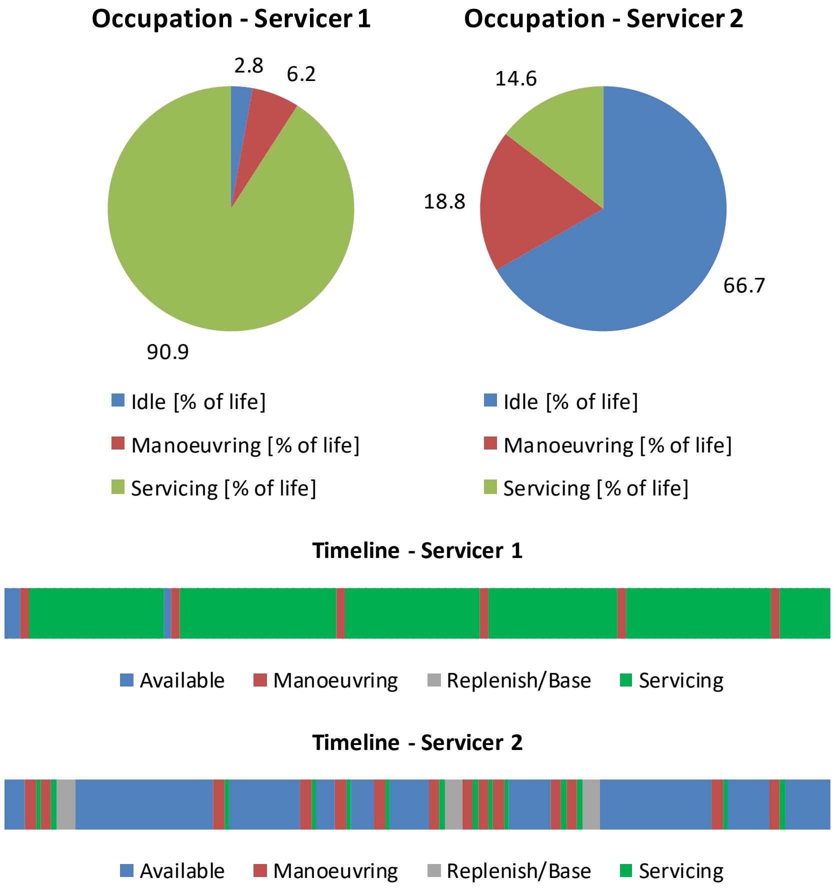
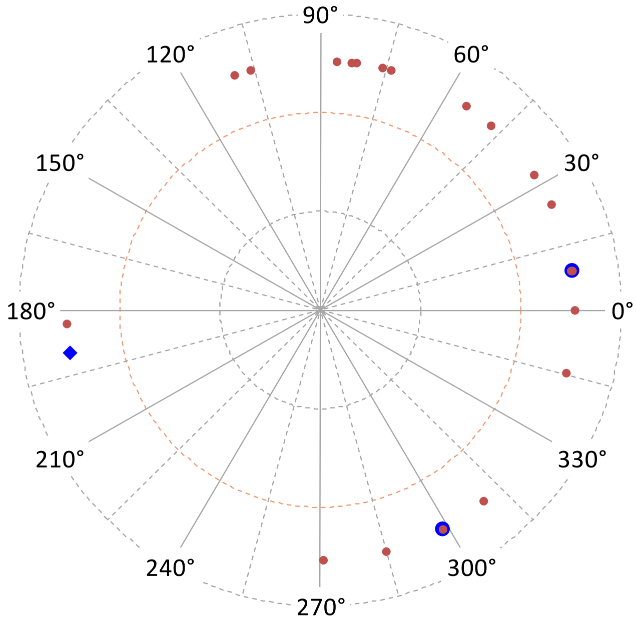


Figure 7-17 – Simulation Dashboard – Population 3 (Part 2 of 3) – Workload and scheduling



Lifetime Extension	
Tickets Open	6
Tickets Assigned	6
Tickets Completed	6
Average Waiting Time [years]	0.348402
Average Manoeuvre ΔV [km/s]	0.11907
Average Propellant Mass [kg]	22.61059

Maintenance and Repair	
Tickets Open	14
Tickets Assigned	14
Tickets Completed	14
Average Waiting Time [years]	0.036986
Average Manoeuvre ΔV [km/s]	0.030389
Average Propellant Mass [kg]	187.0203

Figure 7-18 – Simulation Dashboard – Population 3 (Part 3 of 3) – Location, resources and time

Table 7-5 presents the summary of Case 2, comparing to Population 3 from Case 1 (from which it was generated). The increase in the resources spent by the Servicer are due to the longer extension times suggested by the results from the solution exploration (Figure 7-13 and Figure 7-14). Since the Servicer performing *Maintenance and Repair* has more flexibility in its operation and replenishment of resources, it can provide a larger propellant mass for the Clients.

Table 7-5 – Simulation Summary – Use Case 2 (case comparison)

	Case 1 – Population 3	Case 2
Simulation Time	30 years	30 Years
Clients Simulated	183[c]	20[a c]
Clients Serviced	20[c]	20[c]
Total life extended	55.67 years	89.56 years
Client Average *NPV* (MR)[b]	12.41%	16.65%
Client Average *NPV* (LE)[b]	6.89%	7.28%
Servicer *NPV* (MR)	25.88%	123.86%
Servicer *NPV* (LE)	14.31%	16.35%
Replenishments (Servicer MR)	1 time	3 times
Spent Resources (Servicer)	1635.49 kg	2753.95 kg
Simulation Running Time	116 seconds	9 seconds
Solution Exploration Running Time	-	736 seconds (MR) 440 seconds (LE)

[a] Only serviced Clients from Population 3 – Case 1.

[b] Calculated based only on the serviced Clients

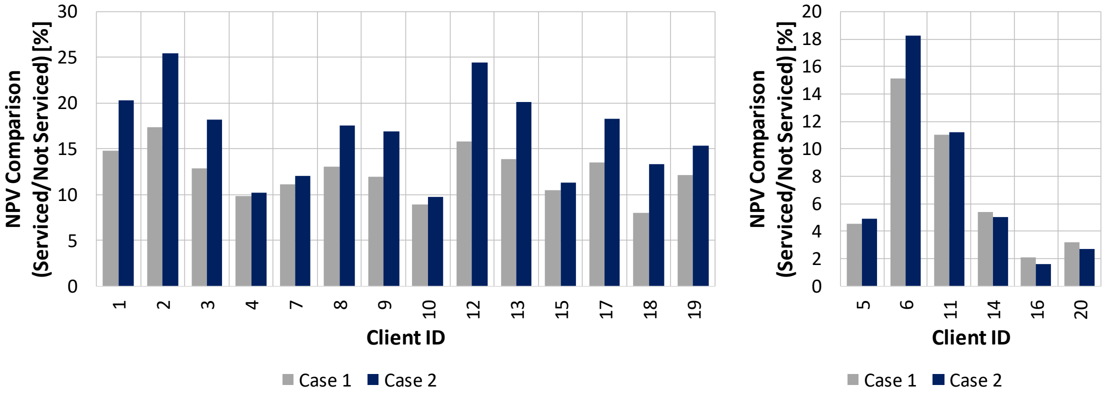
[c] As stated previously, the Clients simulated and serviced in Case 2 are the same Clients serviced in case 1

Case 2 is focused on the Client getting the best outcome from a servicing proposition, while working with the Servicer side for an agreement in the servicing conditions. Compared to Case 1 (Population 3), Case 2 shows improvements for the achieved profits (*NPV*) for all the applications. The improvements in *NPV* for Case 2 (Table 6-5) are related to the adjustment of servicing conditions (*Client Life Extension* and *Servicing Trigger Point*). Although the difference ranges from <1%, for *Lifetime Extension*, and over 4%, for *Maintenance and Repair*, this value reflect the average for all the serviced Clients. It must be noted that the improvements in *NPV* for each specific Client satellite can range above those values as it is presented in Figure 7-19. This improvement was possible due to the use of the Solution Exploration feature. As effect of this change, improvements on the *NPV* achieved by the Servicer must also be highlighted.

The number of Clients simulated does not have a direct influence herein since the Clients serviced in Case 1 are the same Clients serviced in Case 2, but with different servicing parameters. The main improvements in the *NPV* for the Servicer offering refuelling comes from the amount of resources offered/spent (directly dependent on the life extension contracted).

The values indicated in Table 7-5 are the average *NPV* for all the serviced Clients of a given application. Figure 7-19 shows the comparison of the *NPV* between both cases for all the serviced Clients.

The lower *NPV* in Case 2 compared to Case 1 (for Client 14, Client 16 and Client 20) are mainly related to the scheduling and resources management to accommodate the servicing of another Client prior or after. It is important to highlight that, despite some Clients performing with a lower *NPV* in Case 2, the overall *NPV* for the fleet improves as indicated in Table 7-5.



(a) (b)

Figure 7-19 – *NPV* Comparison – Case 1 and Case 2 – (a) Maintenance and Repair (Refuel), (b) Lifetime Extension

Although the objective of this case be the improvement of the Clients servicing conditions using the Solution Exploration, this was limited to a single use of this feature of the framework. It should be noted that the use of the Solution Exploration allows the user to learn from a given case and its main conditions, leading to subsequent explorations until a desired result is achieved (e.g. *NPV*). The current case focuses on exploring an intermediary solution between the conditions (life extension and servicing time) offered by the Servicer operator in Case 1 and a potential improvement of the Client operator side suggested by the single use of Solution Exploration.

Additionally, is important to note that the *NPV* achieved by the Servicer in Case 2 for refuelling can be discussed with a more conservative approach. The replenishment operations are expected to consume a portion of the Servicer's *NPV*, which will dictate if the case can be that profitable or a more limited return would be the case. This can also reflect in a different resource management. The *NPV* increase for the Clients from Case 1 to Case 2 could be explored with the main constraint of keeping at minimum the amount of resources spent (used to refuel the Clients).

7.2.3 Use case 3 – Multiple operators and multi-applications

This case examines the scenario where unplanned external Clients may request emergency servicing in an established servicing environment, demanding the Servicer capacity of offering multiple applications.

From Use Case 2, in which a Servicer was pre-contracted to an exclusive Client operator, Use Case 3 adds up considering an additional External Client operator requesting ad-hoc services. The External Client operator is assumed to not have a dedicated servicing contract, being the servicing request due to the partial failure of a satellite.

7.2.3.1 Parameters

Since the main population for this case is based on the population of Use Case 2 (Main Client operator), The assumptions for life extension are not changed in this case. To this population is added a number of Clients (Sample 2 from Appendix H), considered to be the External Clients. The External Clients are selected based on the failures, as identified in SpaceTrak database. Therefore, the servicing conditions are kept the same for the Main Clients and adjusted/filtered for the External Client (flowchart in Figure 7-20). The Servicer is assumed to start the operation as planned/defined in Use Case 2 and is assigned as necessary to Clients of the Main and External operators. For this use case, it is assumed that the Servicer for refuelling is capable of performing addressing multiple/different applications [45].

- **Applications considered**
    - *Rescue and Recover*, *Lifetime Extension*, and *Maintenance and Repair* (Refuel)
- **Rationale**
    - Consideration of OOS by operators outside the mainstream of life extension and without a dedicated contract with a specific Servicer operator.

- **Population simulated**
    - Sample 1 (Population 3) with addition of Sample 2 (Appendix H)
- **Assumed inputs and constraints**
    - *Pre-assignment of OOS applications*: *Rescue and Recover* (for selected Clients) and multi-application (for Servicer)
    - *Initial Servicer intended profit*: As defined in Case 1 and Case 2 and negotiated with Client side.
    - *Initial servicing trigger*: Failures and previously defined servicing times (Case 2)
    - *Servicer operational constraints*: Starting/launched at the time of the first servicing mission, unconstrained replenishment of resources (if applicable), non-extendable life, multiple applications.
    - *Client operational constraints*: Based on limitations imposed by other Clients of the fleet.

7.2.3.2 Methodology/Steps

Use Case 3 considers a view from both Client and Servicer sides. An additional sample is included to explore the occurrences of failures of Client satellites of a second operator which could be remediated using a Servicer. This second Client operator, defined herein as External Client, represents an external request for servicing from the main servicing contracts discussed in Case 1 and Case 2. Therefore, it is considered that the External Client does not have a previously arranged agreement for servicing.

Although this case also uses the Client presented in Case 2, the focus is on the additional sample of the External Clients included in the simulation to explore servicing application of *Rescue and Recover*.

The steps consist of a simplified iteration of the simulation conditions and are described as follows:

1. Definition of additional [14] External Clients with a pre-defined/historic failure or stochastic probability of failure (SpaceTrak filters in Appendix H);
2. Definition/enabling of Servicers with multi-application capabilities (*Maintenance and Repair* Servicers);
3. Simulation of the additional sample in the same environment/conditions as Case 2;
4. Filtering [15] and minor iterations of servicing time and extension (for Clients of the main fleet) to accommodate the rescue of External Clients of the secondary fleet;
5. Final run.

The steps described previously are illustrated in the flowchart of Figure 7-20.

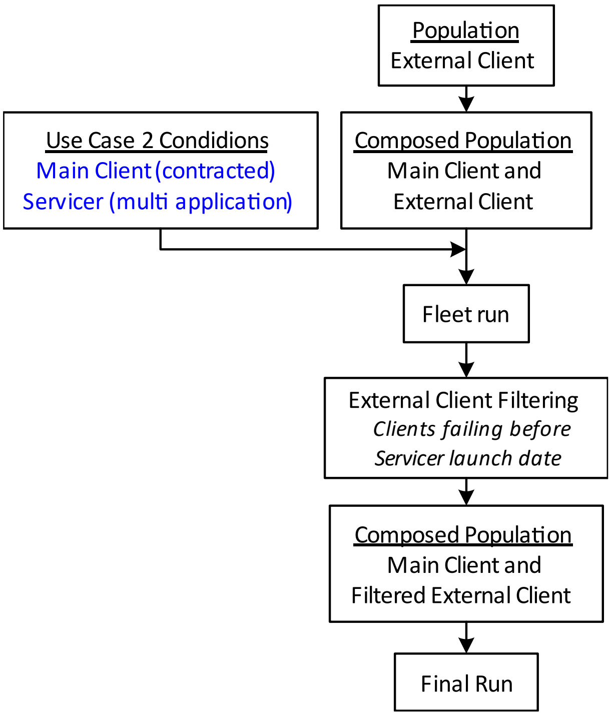


Figure 7-20 – Flowchart (Use Case 3) – Main Client and External Client population definition and filtering

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[14] Sample defined based on SpaceTrak database, considering satellites that suffered anomalies that could be fixed by a Servicer.

[15] From the sample selected, are filtered any Client satellites with expected servicing time (due to failure) prior que launch date of Servicer 2 (assumed to be compatible with multi-application). Since the Servicer considered herein is dedicated to the main fleet, launching it earlier have direct effects on the operation of the Servicer and the services provided. Such condition could be bypassed by the refuelling of Servicer resources, however, the current case would still be limited by the operational time of the Servicer, even if refuelled.

The information in blue represent the simulation parameters from the Main Client operator. This information comes from Use Case 2. The filtering process is applicable only to the External Client, as described in the in the step 4.

7.2.3.3 Results and Discussion

Assuming the Client operator from Case 2 has decided to contract a dedicated OOS solution provided by Servicer from Case 1, extra conditions are added. An External Client operator is considered to need to use servicing solutions for emergency cases but does not have a dedicated servicing contract. This highlights the possibility of arrangements in an OOS eco-system, considering a Servicer with capabilities for multiple applications.

Clients from Case 2 are considered as priority by the Servicer operator due to the assumption of a dedicated contract between Client and Servicer operators. Therefore, failures (from the External Client) happening at times while the Servicer is assigned are left waiting until the Servicer is available. This assumption is used to simplify what could occur in a real-life case where a failure can unfold a longer discussion and negotiation between operators (main and External), depending on the emergency to remediate the anomaly/issue.

The dashboard (Figure 7-27 to Figure 7-29) shows the summary of the simulation for all the satellites of both fleets. Client 21 and Client 22 are the satellites of the External Client operator which were able to be serviced by the multi-application Servicer.

The relatively high values indicated by the rescued External Clients (Client 21 and Client 22 – Figure 7-21) are due to the metric comparison to the failed/anomalous condition. This becomes more evident in the specific metrics comparison (from Figure 7-22 to Figure 7-24), specifically where the behaviours of the metrics change abruptly due to the failure. The failed/anomalous condition of those Clients prevents them from operating at their full capability, therefore limiting the value the operator gets from those systems.

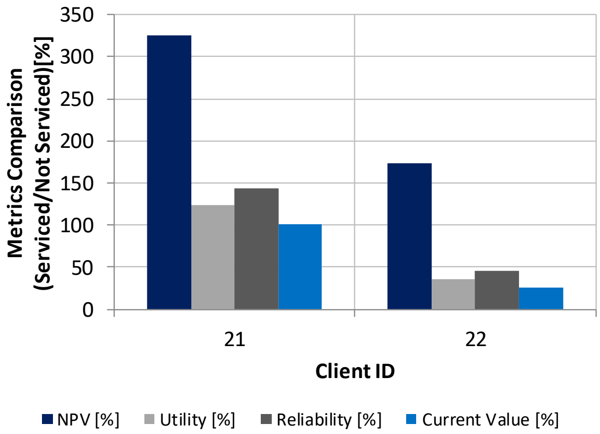
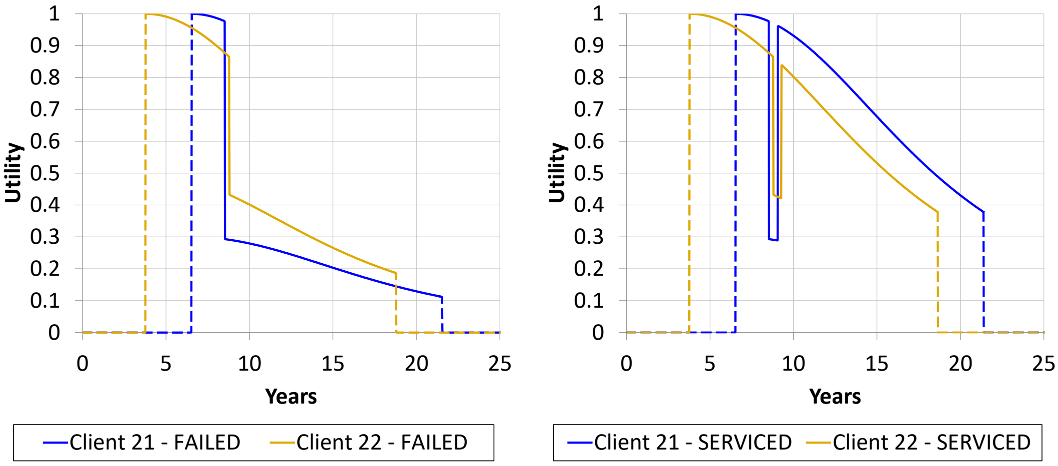
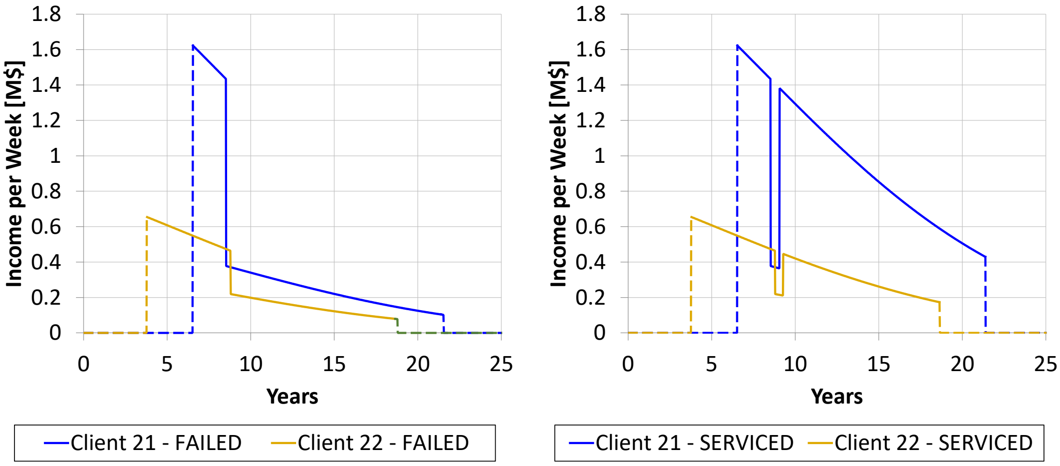


Figure 7-21 – Metrics Comparison – Rescued Clients (External Client)



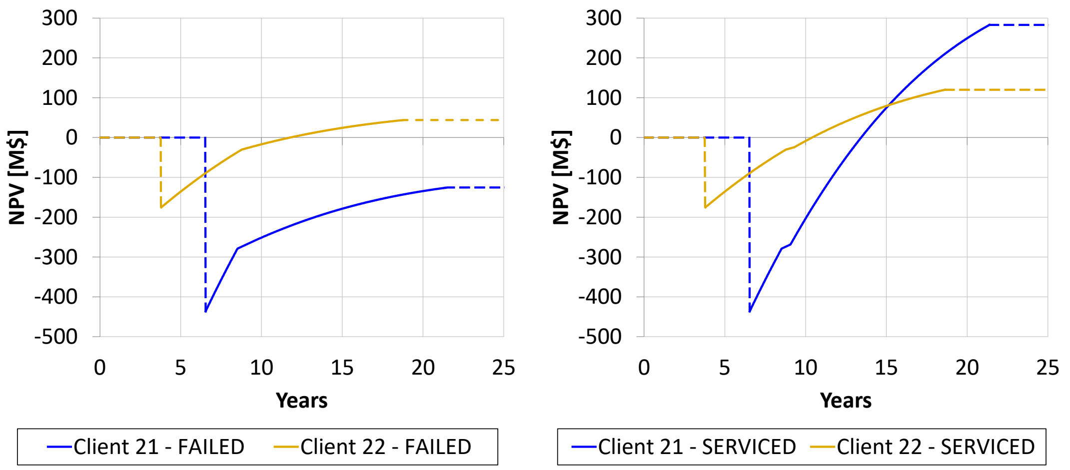
(a) (b)

Figure 7-22 – External Client – Failed Clients (*Utility*) – (a) Not serviced and (b) Serviced



(a) (b)

Figure 7-23 – External Client – Failed Clients (Income Capacity) – (a) Not serviced and (b) Serviced



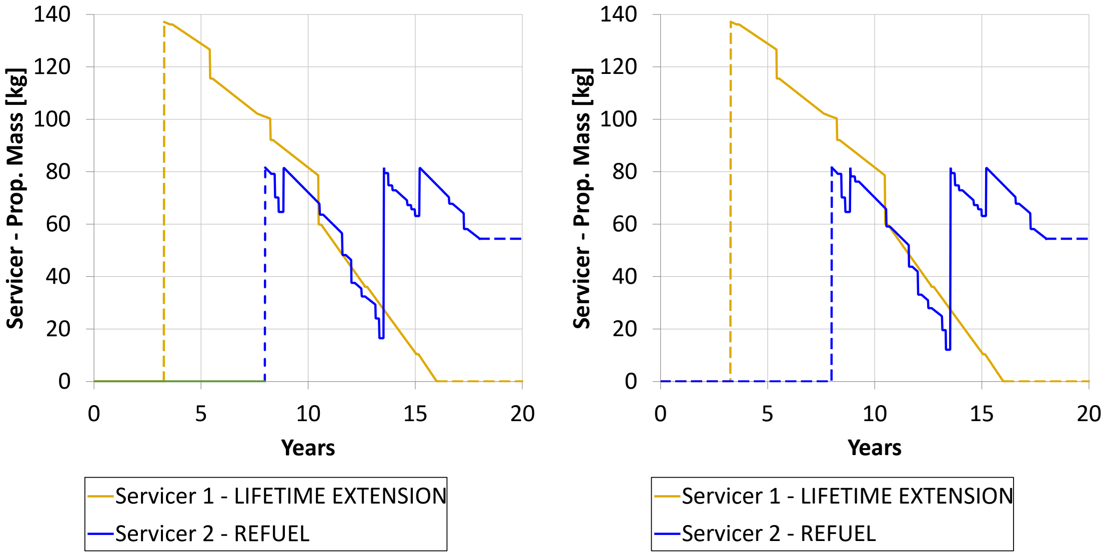
(a) (b)

Figure 7-24 – External Client – Failed Clients (*NPV*) – (a) Not serviced and (b) Serviced

From a Servicer perspective, this represents additional opportunities to provide a suitable service to an External Client during periods of availability/idle state as identified in the two previous cases. The servicing of External Clients could represent a higher profit margin but brings the need to track closely the resources used (Figure 7-25) for the External Clients, while maintaining the primary Clients with a minimum of disruption. The framework would also assist a Servicer operator at the stage discussed in Case 1, prospecting for possible Clients, and aiming to offer more responsive types of servicing for cases of potential failures, either from the primary or from an External Client.

The main metric analysed from the Servicer side is the available resource (propellant mass) the system has available with time. Since no propellant transfer is expected to be performed in a rescue operation, the only resource spent is the propellant to manoeuvre to the position of the failed Client. This is presented in Figure 7-25, in which minor differences can be observed for the usage of propellant. The rescue operations are presented more clearly in Figure 7-26 when looking to the Servicer timeline, in comparison with the case of single application. After the first replenishment operation, the Servicer spends less time in an Idle state as it responds to two consecutive Client failures (External operator). The subsequent operations have minor or no disruptions, not affecting any previously contracted servicing.

For this case, the scheduling, rather than the amount of resources available, is the main limiting factor to discuss about the additional services. Once more, a series of decisions would take place for the definition of how such an operation would happen. The emergency of the failure would dictate the level of responsiveness a Servicer would have to provide. Since the main Client is considered priority for assignment and manoeuvre, the parameters for the phasing manoeuvre (discussed in Chapter 5) are considered for normal priority. Should the failed Client request a high priority rescue, the conditions would change how a Servicer respond and the effect on the main contracted fleet.



(a) (b)

Figure 7-25 – Servicer Usage (Propellant mass m_p) – (a) Case 2 and (b) Case 3

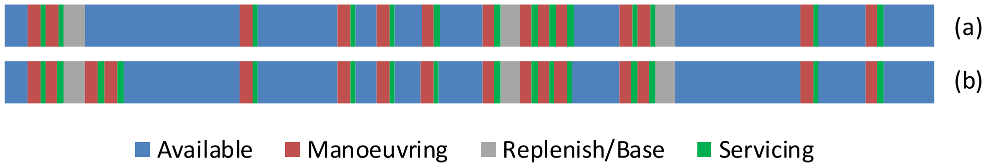


Figure 7-26 – Servicer Operational Timeline – (a) Use Case 2 (Single Application) and (b) Case 3 (Multiple Applications)

For the Servicer, any time spent in an idle condition represents a non-ideal state for the operator aiming for financial profit. This was discussed in Chapters 5 and 6, indicating how the system condition and financial conditions degrade with time. For the rescued

Clients, the characteristics of the failure (severity/loss of capacity and time of occurrence) will drive the benefits and challenges of rescuing/servicing the system.

The dashboard for this use case is presented from Figure 7-27 to Figure 7-29.

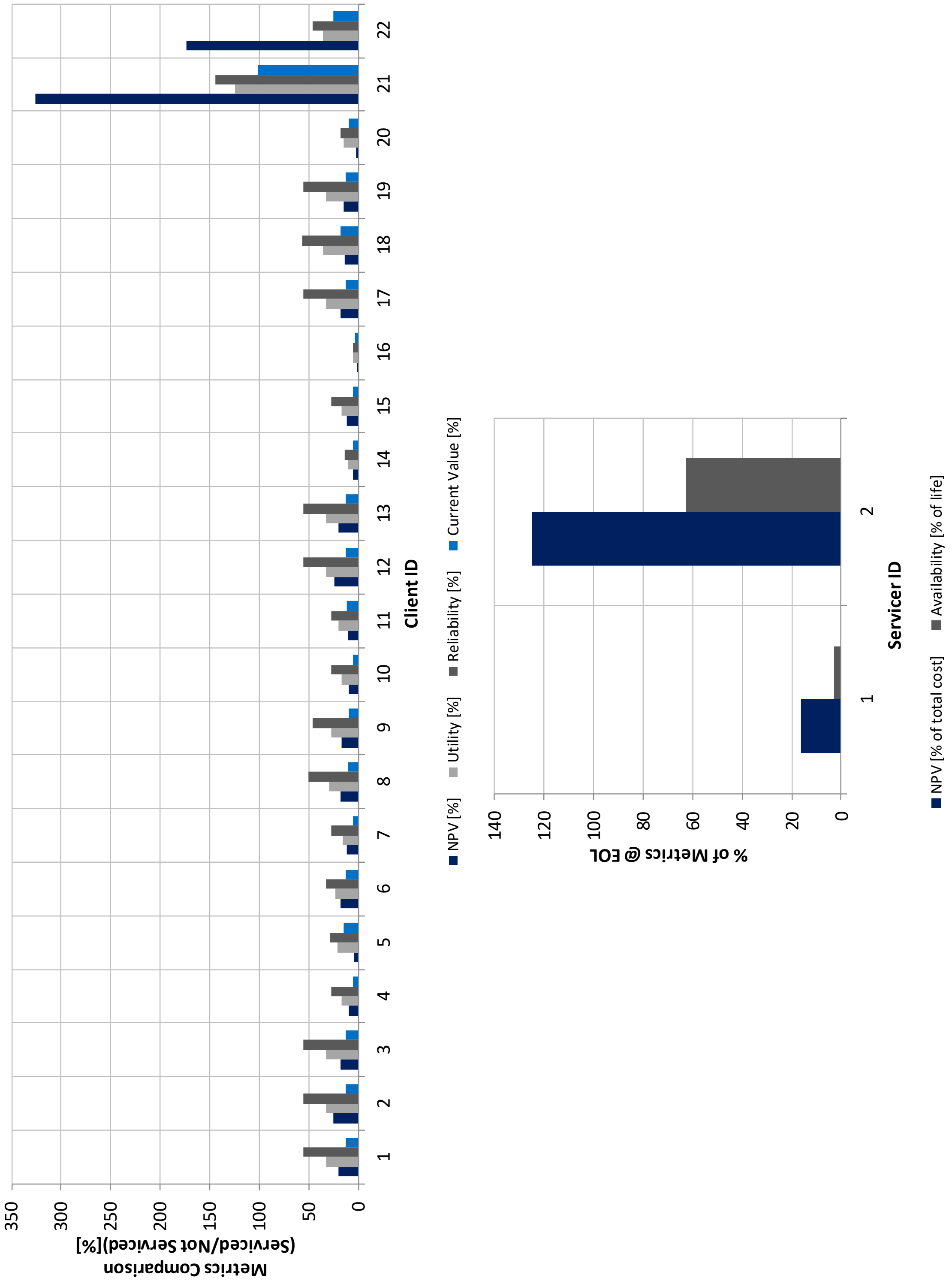


Figure 7-27 – Simulation Dashboard – Multiple Operators (Part 1 of 3) – Comparison / Trade-offs

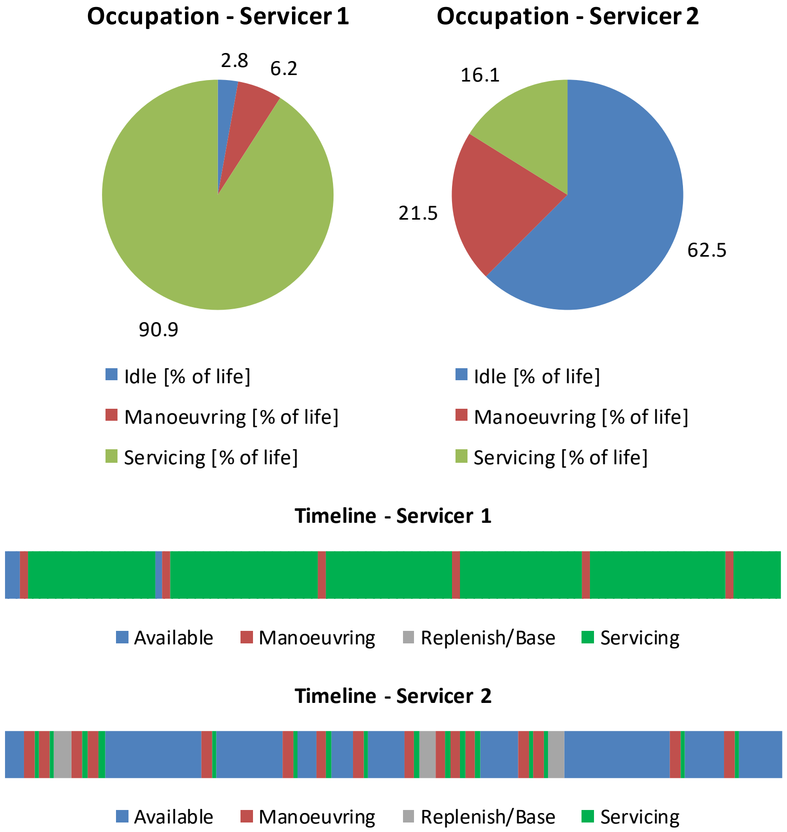
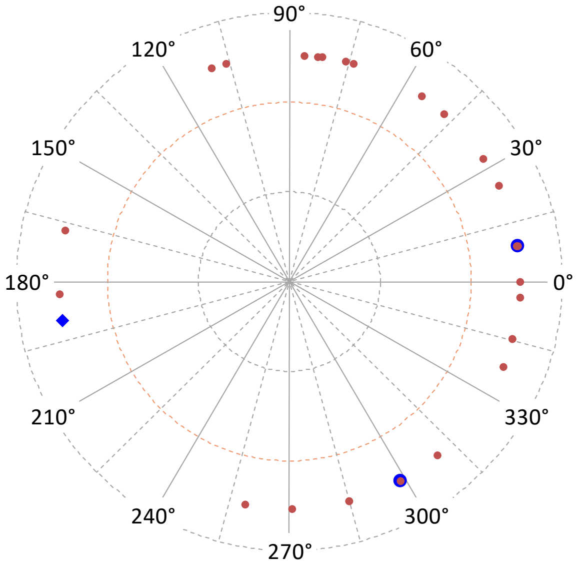


Figure 7-28 – Simulation Dashboard – Multiple Operators (Part 2 of 3) – Workload and scheduling



Lifetime Extension	
Tickets Open	6
Tickets Assigned	6
Tickets Completed	6
Average Waiting Time [years]	0.348402
Average Manoeuvre ΔV [km/s]	0.11907
Average Propellant Mass [kg]	22.61059

Maintenance and Repair	
Tickets Open	14
Tickets Assigned	14
Tickets Completed	14
Average Waiting Time [years]	0.036986
Average Manoeuvre ΔV [km/s]	0.031574
Average Propellant Mass [kg]	187.1959

Rescue and Recover	
Tickets Open	6
Tickets Assigned	2
Tickets Completed	2
Average Waiting Time [years]	0.29726
Average Manoeuvre ΔV [km/s]	0.017104
Average Propellant Mass [kg]	2.597876

Figure 7-29 – Simulation Dashboard – Multiple Operators (Part 3 of 3) – Location, resources and time

Additionally, this highlights the use of the framework to enable the discussions between different Client operators (Primary and External) in situations such as for this case. Although not directly implemented in the framework, the results could be used as a background for the leasing of the dedicated Servicer, theoretically resulting in an attractive condition for three parties: the two Client operators and the Servicer operator.

From the overall results for this case, no major drawbacks are observed for the main contracted Client fleet, or the servicing provider. This can be checked comparing the results in Figure 7-18 and Figure 7-27. A summary of the results from Case 2 and Case 3 are presented in Table 7-6.

Table 7-6 – Simulation Summary – Use Case 3

	Case 2	Case 3
Simulation Time	30 Years	30 Years
Clients Simulated	20	26 [a]
Clients Serviced	20	22
Total life extended	89.56 years	89.56 years
Clients Rescued	-	2
Client Average *NPV* (MR) [b]	16.65%	16.62% [c]
Client Average *NPV* (LE) [b]	7.28%	7.28% [c]
Servicer *NPV* (MR)	123.86%	124.74% [d]
Servicer *NPV* (LE)	16.35%	16.35%
Replenishments (Servicer MR)	3 times	3 times
Spent Resources (Servicer)	2753.95 kg	2761.60 kg
Simulation Running Time	9 seconds	13 seconds

[a] Primary Clients and External Clients

[b] Calculated based only on the serviced Clients

[c] *NPV* from servicing only from Primary Clients

[d] *NPV* from servicing Primary Clients and External Clients

Nevertheless, it must be noted a small difference in the Average *NPV* for *Maintenance and Repair* in Case 3. In this case, Servicer 2 manoeuvres from the position of Client 22 (External Client) to refuel Client 4 (Primary Client). In Case 2, the manoeuvre to service Client 4 is made from the refuelling base, in a different orbital slot. This reflects in the Servicer spending more propellant in Case 3, therefore increasing the charged price for the refuelling of Client 4. In Case 2, Client 4 achieved an improvement in the *NPV* of 10.21% while in Case 3, Client 4 the *NPV* improvement is of 9.84% because of the higher servicing charge. This reflects a condition where the main Client and the

External Client would discuss a proper measure to compensate such reduction in the *NPV*, if necessary. For example, the primary Client could charge the External Client the “lost” *NPV*. Additionally, a more refined assumption for the costing/charging of the Servicer time and resources will also affect potential negotiations between a pre-contracted and an External Client. Once more, the framework plays the central role allowing the involved operators to explore the outcomes of potential agreements and/or compensations.

The nondeterministic nature of a failure brings more complexity to the simulation and decision. Herein, historic cases of failure coming from SpaceTrak were used to define the parameters for the additional sample. The framework could still be used considering the stochastic mode (described in Chapter 5) to explore the potential demands of rescue operations.

7.2.4 Use case 4 – Servicing mid-term future and persistent platforms

This case examines the scenario where a more established servicing environment is available for operators to choose more advanced servicing applications.

For this case, a Client operator would be using the framework to explore the adoption of a satellite architecture based on a serviceable Persistent Platform. Such platforms would be designed for a longer life, compared to today's standards, and the payload would be upgraded through life. The results for a Persistent Platform are compared to results for architectures based on Standard Platform, conventional satellite architecture as used today.

From a Servicer perspective, the use case highlights important characteristics of logistics and scheduling, critical points to be considered due to the potential degradation of the upgradable platforms with time.

Since this case covers areas of servicing still under development and with limited information available publicly, a set of assumptions is made regarding the characteristics of the upgradable payload and the costings related to the servicing operation. The implications of these assumptions are also discussed in the last subsection of the current use case.

7.2.4.1 Parameters

Due to the current the limit of information about characteristics of upgradable payloads, the parameters for this use case are based on a more generalised assumption process.

The Client population is composed of satellites with launch expected for the next 7 years, as presented in Table 7-2. The rationale for this selection is to consider that the operator would still be able to decide now for a serviceable architecture (Persistent Platform), assuming upgradable payloads were commercially available today.

The characteristics of the upgradable payload are assumed using as reference the current mass budged for the conventional payload of a Client satellite, illustrated in Figure 7-30. This assumption also facilitates the estimate of income generation capacity of these upgradable payloads and, lastly, their costs.

For simplicity, the servicing is defined to happen after the first half of the operational life of a Persistent Platform. This assumption allows the comparison of the Persistent Platform architecture to a Standard Platform architecture.

Lastly, the Servicer characteristics are based on two of the commercially available options, MEV and RSGS [45,169]. Although these Servicers are intended specifically to life extension, their applicability to cases of Payload Augmentation is a characteristic pursued by their operators. Therefore, characteristics of lifetime and payload capacity are used as reference for the estimation.

- **Applications considered**
    - *Maintenance and Repair* (*Payload Augmentation*)
- **Rationale**
    - Consideration of OOS by operators changing the systems' architecture towards more service-friendly configurations and persistent platforms.
- **Population simulated**
    - Sample 3 – Future expected launches with modified lifetime.
- **Assumed inputs and constraints**
    - *Pre-assignment of OOS applications*: *Maintenance and Repair* (*Payload Augmentation*).
    - *Initial servicing trigger*: Minimum *Utility*/specific time in life.
    - *Servicer operational constraints*: Starting/launched on the position of the first servicing mission, no replenishment of resources, non-extendable life, single application.

7.2.4.2 Methodology/Steps

Part of the steps to simulate this case would be optional in a real-case analysis since the user will have the complete knowledge of the systems to be operated. The steps herein are to extrapolate or estimate the satellites' parameters to what would be expected of a Persistent Platform. Such platforms consider a baseline system operating for a given time (normally longer than the usual life of a Standard Platform satellite), allowing the decision to upgrade/improve through life.

Therefore, the main steps are related to the estimation of propellant mass for the longer operation (consider herein as twice the life found in database) and estimates of the payload cost, used as reference for the calculation of the additional payload.

The steps are defined as follows:

1. Simulation of the conditions "as is" (Standard Platform), with parameters extracted from database;
2. Calculation (Figure 7-30) of total mass values to consider the additional propellant mass for the new design life, herein considered as double the life of a Standard Platform;
3. Simulation of Persistent Platforms being serviced at a given time defined by the user.
4. Adjustments of Servicer parameters for cost, life and available resources;
5. Final run.

Figure 7-30 presents a diagram of the process to use the Client main parameters of a Standard Platform to estimate the characteristics of a Persistent Platform and the payload characteristics. Using the two flows presented in Figure 7-30 it is possible to estimate:

(a) the cost of a persistent platform;
(b) the payload income generation capacity.

Both parameters are necessary for the assumptions used herein due to the current limitation of public information about additional payloads.

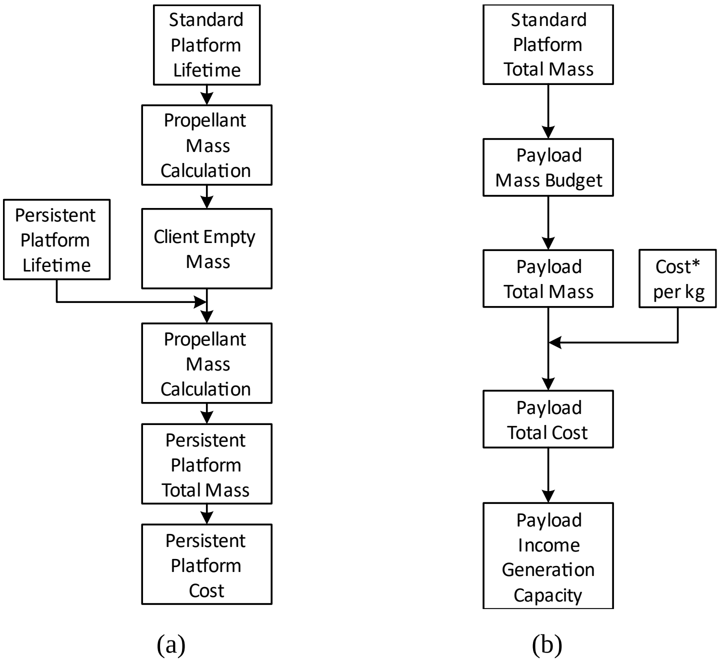


Figure 7-30 – Persistent Platform estimation process – (a) Total Mass and Cost, (b) Payload Mass and Income Generation Capacity

The income generation capacity at the beginning of life of a Persistent Platform is assumed to be similar to the Standard Platform. As described in Chapter 5, the income generation capacity can be defined by the TTBE and discount rate. For this case, the TTBE for Persistent Platforms is defined to represent a similar income capacity to the Standard Platforms at the beginning of the operational life. As Persistent Platforms are defined herein with a longer life (twice the life of a Standard Platform as defined for this case), using the proportion of TTBE (e.g. 40% of t_{life}) would reflect in a satellite with potentially decreased income generation capacity, with a later return on investment.

7.2.4.3 Results and Discussion

This case explores a mid-term future for servicing solutions related to changes in the payload capacity, payload augmentation and persistent platforms. Herein, it is assumed that operators more open to adoption of servicing solutions would be able to commission platforms with relatively longer operational life, making use of servicing to upgrade/improve through the life, based on the demands and conditions encountered in the future.

Considering that the future capabilities of payload augmentation and changes of the system are still under discussion and definition, a list of assumptions is considered for the simulation.

This case follows a similar rationale to Case 2, where Client and Servicer operators use the framework to discuss a balanced condition for both sides, to achieve a mutual benefit. Therefore, it is considered that the Servicer is dedicated to a given fleet, under a contract. Cases of payload augmentation on-demand are discussed in the commercial developments and literature but still present points to be developed or matured. On demand augmentations would suffer a large influence of the other cases discussed in this chapter, mainly depending on the success of servicing to evolve systems to a (quasi) standardised-type of platforms.

Considering that in this case the Servicer would be in most of the life in an idle condition, it would be desirable to minimise such characteristics as discussed in the previous cases. Additionally, it is assumed that the Servicer is launched with all the additional payloads necessary. The time for which such subsystems are exposed to the space environment before the final installation is a concern the Servicer operator would look to minimise as well. In the same line, the launch of a Servicer too close to the launch date of a Client would invalidate or reduce any potential benefits of a through-life upgrade. Both conditions could be simulated in the framework once the main constraints are defined.

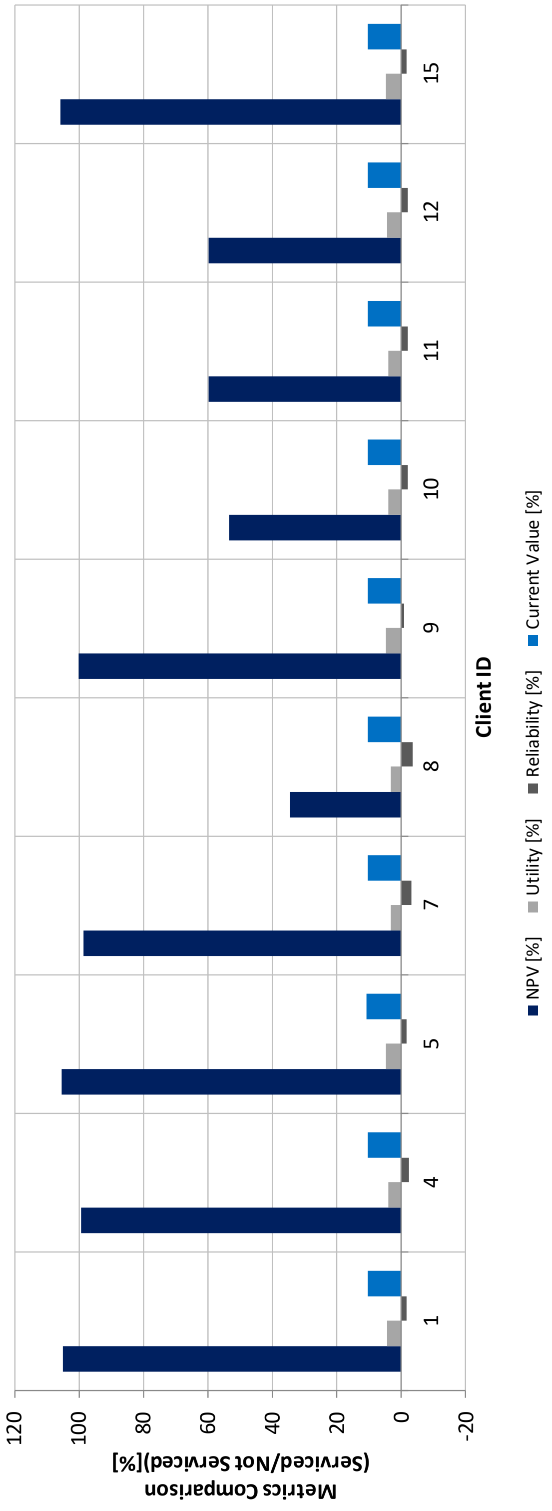
For simplicity, it is assumed that the cost of the additional payload varies proportionally with the cost of the Client satellite. Such price will define a direct charging price the operator would pay and how the system would perform financially based on the new cost of the Client satellite. One final assumption is that the new subsystems installed would restore the operational capacity/usefulness of the satellite to BOL levels. A more precise costing would still consider the mass of the additional payload, mainly from a logistics' perspective, but would also incorporate characteristics of the payload, e.g. communication, broadcasting, observation, data collection.

The sample of Clients used in this case consider future expected launches. In this way, the operator, by using the framework, would have a proper decision time to consider servicing. However, this sample is considered with a modified lifetime (double), mainly affecting the amount of propellant and cost. The servicing time can be defined in the framework based on the *Utility* value through life or via a specific limit of life for servicing (similar for the cases of extension of life).

For effect of comparison, the Persistent Platforms are compared to the results of the Standard Platform as they come from the database. This could also be used to discuss whether launching a whole new system would be more attractive.

Although Case 4 considers a series of assumptions, it still demonstrates the usefulness of the framework to help define such types of servicing expected to debut in a mid-term future. As servicing becomes a more attractive/affordable solution, the interests of both parties (i.e. Client and Servicer) would help to shape more advanced applications; here, use of the framework will be of key importance.

Still, Case 4 is limited by the assumption that the installed payload would improve the usefulness/capacity of the system up to its maximum (as new). In reality, the incorporation of newer subsystems, mainly responsible for income generation, should be able to surpass the initial designed capability of the satellite. However, such condition would demand a more in-depth analysis of the available subsystems and how they operate. With a given characterisation or proper understanding of how these subsystems work, cases where an upgrade could actually increase the usefulness to higher than the original level are also possible to simulate using the framework.
The dashboard for this use case is presented from Figure 7-31 to Figure 7-33.



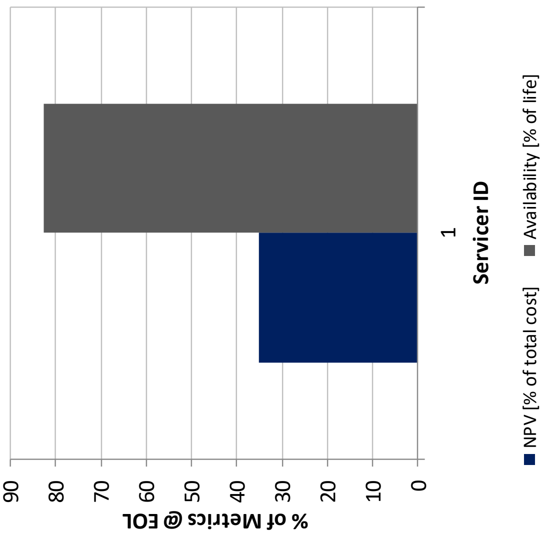


Figure 7-31 – Simulation Dashboard – Persistent Platforms (Part 1 of 3) – Comparison / Trade-offs

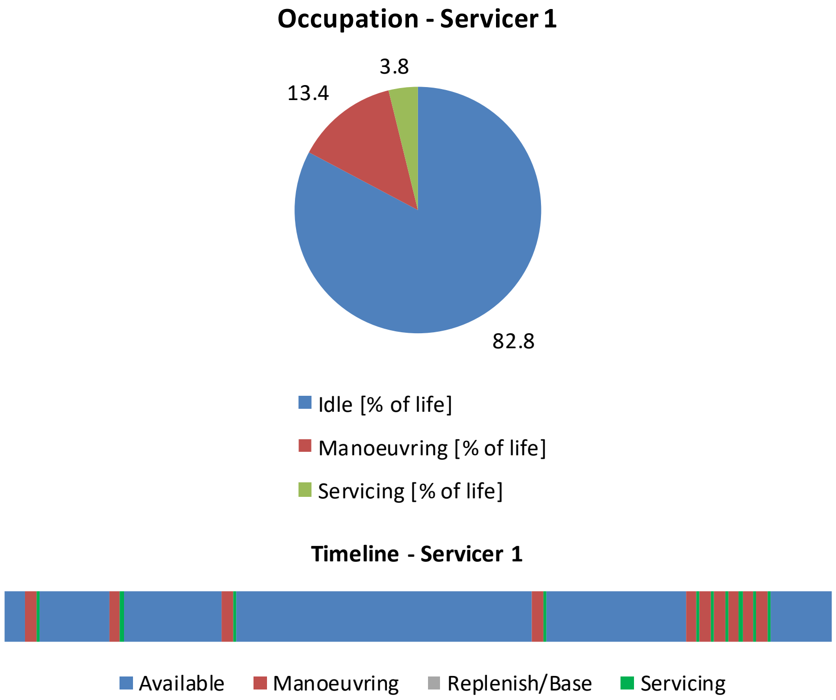
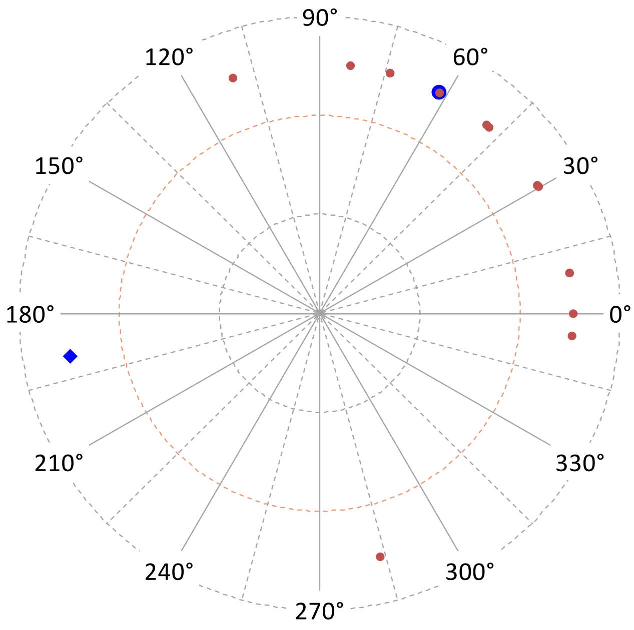


Figure 7-32 – Simulation Dashboard – Persistent Platforms (Part 2 of 3) – Workload and scheduling



Maintenance and Repair	
Tickets Open	15
Tickets Assigned	10
Tickets Completed	10
Average Waiting Time [years]	0.15726
Average Manoeuvre ΔV [km/s]	0.01063
Average Propellant Mass [kg]	1.429668

Figure 7-33 – Simulation Dashboard – Persistent Platforms (Part 3 of 3) – Location, resources and time

Table 7-7 – Simulation Summary – Use Case 4

	Case 4
Simulation Time	40 Years
Clients Simulated	15
Clients Serviced	10
Client Average *NPV* (MR-PA) [a]	82.12%
Servicer *NPV* (MR-PA)	35.19%
Replenishments (Servicer MR)	-
Spent Resources (Servicer)	14.30 kg
Simulation Running Time	17 seconds

[a] Calculated based only on the serviced Clients

The metrics comparison from the dashboard in Figure 7-33 shows the comparison between serviced and non-serviced conditions. However, the decision related to Persistent Platform would encompass a trade-off between the Standard Platform and the new, long-lasting and upgradable system.

Although this would be relevant in a context of a known expected market change, the results for *NPV* of Persistent Platforms (NPV_{PP}) are compared to results for *NPV* of Standard Platform Clients (NPV_{SP}).

The unchanged sample from SpaceTrak is used to simulate a combined program, in which two satellites (Standard Platform) operate consecutively. An example of this consecutive operation is presented in Figure 7-34.

Figure 7-34a presents the *NPV* of *Client X* and *Client Y*, two Standard Platform satellites with similar characteristics, i.e. lifetime ($t_{Life\ SP}$), costs and financial capacities. *Client X* operates in the first half of the period and *Client Y* starts the operation right after the EOL of *Client X*. The cost of the second *Client Y* satellite is discounted based on the discount rate expected/adopted by the operator. Figure 7-34b illustrates the *NPV* achieved by the operator at the end of the operational life of the Combined Program using Standard Platforms (NPV_{SP}).

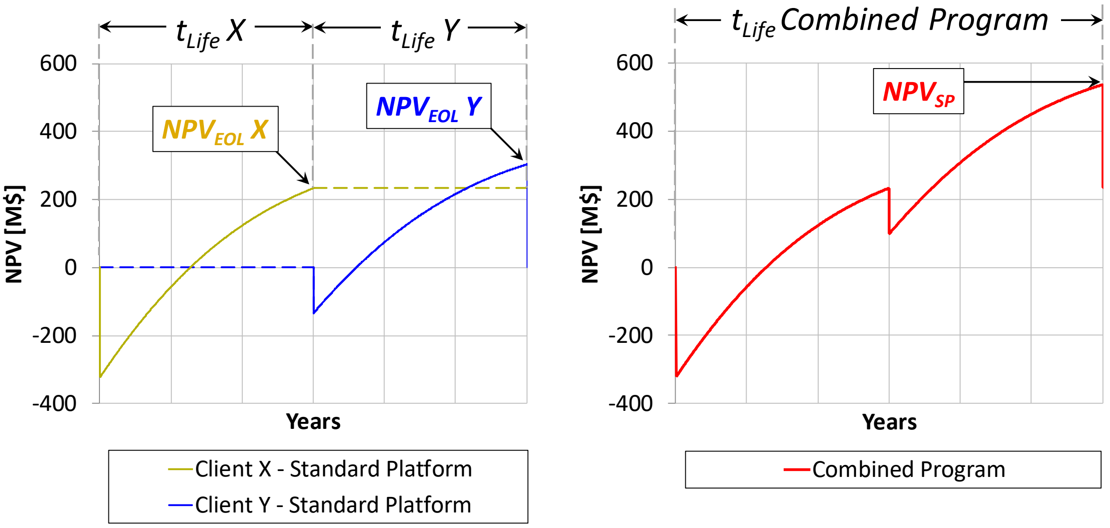


Figure 7-34 – *NPV* for Consecutive Standard Platforms – Combined Program

Table 7-8 presents the comparison of the NPV of Persistent Platform (NPV_{PP}), focus of this use case, to the NPV of the Combined Program (NPV_{SP}) illustrated in Figure 7-34. For more clarity, the results presented in Table 7-8 are also illustrated in Figure 7-35.

Table 7-8 – *NPV* Comparison – Standard satellite and Persistent plartforms

Client ID	Condition	NPV_{SP} [M$] [a]	NPV_{PP} [M$] [b]
1	Serviced	537.657	1023.128
2	Original	349.111	301.257
3	Original	354.830	306.881
4	Serviced	308.256	517.009
5	Serviced	529.732	997.589
6	Original	343.582	295.985
7	Serviced	274.959	457.955
8	Serviced	679.394	446.787
9	Serviced	638.384	1187.181
10	Serviced	534.586	619.004
11	Serviced	534.662	644.752
12	Serviced	557.310	675.208
13	Original	302.345	257.920
14	Original	357.639	271.469
15	Serviced	526.980	993.281

[a] *NPV* of a Combined Program using two consecutive Standard Platform Clients.

[b] *NPV* of a single upgradable Persistent Platform Client.

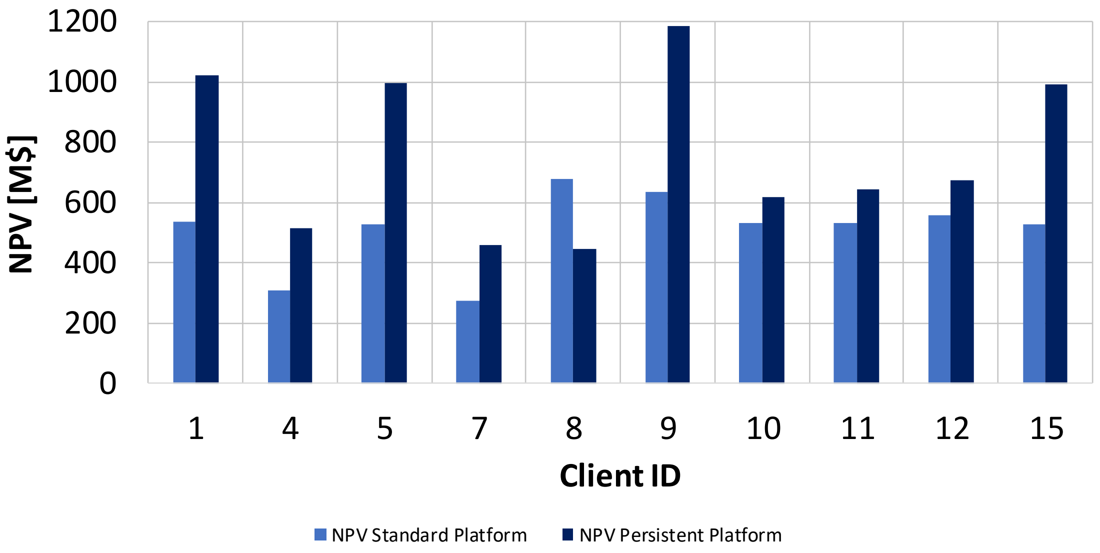


Figure 7-35 – *NPV* Comparison – Standard Platform and Persistent Platform – Serviced Clients

It must be noted that Client 8 presented a better result using two consecutive Standard Platforms rather than one upgradable Persistent Platform which could be linked to different factors. The short operational life, the low total cost and the high income capacity could be the reason of such a better performance as the Standard Platform version of the satellite. The shorter life of the satellite, as a Standard Platform, reflects in a less impactful increase in the total cost of the Persistent Platform version of Client 8 (as illustrated in Figure 7-30). Also, the changes in the income capacity for the Persistent Platform version results in a longer time for the return of the investment. Additionally, the cost of the payload installed on the Persistent Platform version of Client 8 can also help to justify the results presented in Figure 7-35. For all of the mentioned reasons, the framework can be used for a fine adjustment of the operational life, revenue income generation capacity and servicing conditions.

The performance of Persistent Platforms is linked to technical characteristics of the system, the capability of the new subsystem installed, their overall costs and the changes in the demand of the Client final user. Therefore, estimating this would require a more refined definition of the scenario for the simulation in the framework.

It is expected that the earliest installation of a payload would bring more benefits to the system due to its assumed better capacity. However, the main rationale for the case of persistent platforms is to launch a system and, through its life, upgrade the capacity with subsystems not available or non-existent at the moment of manufacturing/launch, or even to be able to adapt to changing markets by modifying the payload over time.

In this way, the earliest installation would be a fundamental constraint in this case. This point is also to be looked at by the Servicer operator in order to give leverage to its system in providing the close-to-latest technology for additional payloads.

Should the user find it necessary, the financial conditions described in Chapters 5 and 6 (TTBE and discount rate) can be updated at the time of the payload upgrade to represent an expected change in the market. Both variables define the capacity of income generation which, with addition of a new payload, is updated based on the value added by this subsystem.

7.3 Conclusions

For the cases approached in this chapter, a total of 588 satellites (Client and Servicer) were checked against different servicing conditions using the framework. The conditions were limited to potential interests in OOS based on the current trends and developments.

The use cases presented in this chapter provide a reasonable coverage of potential scenarios to be explored with the framework. General and specific populations, planned and on-demand cases of servicing, current and future cases are all simulated to anticipate potential decisions the user (Client, Servicer of both) would face. Each case has been discussed individually, indicating points where more refinement could be made using the framework.

The overall methodology in this chapter was used with the objective of demonstrating the framework, in parallel with analysing given cases of OOS in the current industry context. The summarised methodologies presented for each individual case also give guidelines for other, more particular analyses, the user may want to explore.

Specific points about the limitations of the framework are discussed in the next chapters. However, if the user is able to abstract their main requirements and constraints using the implemented inputs/variables, the analysis of OOS encompassing the full relation of Client and Servicer can be performed.

Although the results presented for each case show potentially attractive options for both Client and Servicer, it is important to highlight that those are a fraction of the entire samples used. This demonstrates that, there will still exist cases in which OOS will not be a viable solution for either one or both sides, and the framework is able to identify them. It is still up to the user, by considering their objectives, to re-arrange parameters, change assumptions and constraints in order to analyse in detail if an expected condition will be totally beneficial or not.

Both the demonstration of the framework, the guidelines of using it and discussion of the results help to meet the proposed objective of the research.

8 Final Discussion and Conclusions

This chapter presents the final discussion of the current research based on the main results and individual discussions from previous chapters. It is subdivided in four main sections with focus on the structure of the research, the modelling of the framework, simulations to be explored and limitations of the framework and of the research.

8.1 Structure

The research (and consequentially the framework) is organised in a systemic way from a higher level of information for the concepts of operation for OOS. This enables a fairly comprehensive view of the different applications of servicing (Chapters 1 and 3), while still keeping it manageable under a single-operated tool (Chapters 5 and 6). Such systemic structure also allows a quick and concurrent iteration between the two sides of OOS, one of the main lacks identified for OOS implementation (Chapters 3 and 4).

As future different applications of OOS come to implementation, or more specific/concrete concepts of operation are outlined for the current applications, the structure still allows a quick implementation due its top-down arrangement, mainly characterised by the taxonomy suggested in Chapter 2.

On the other hand, it can be limited for steps beyond the capabilities of OOS. Cases of On-Orbit Manufacturing (OOM – briefly discussed in Chapter 2) are part of the realm of capabilities currently being pushed by the industry. Although OOS and OOM overlap in the majority of their functions (Chapter 3) and objectives, OOM can be more drastic/disruptive in its changes (industry, concepts, markets). Still, the main steps to achieve an OOM environment will necessarily depend on the successful implementation of OOS, which is one of the main points the current research aims to support with its structure.

8.2 Modelling

Following the structure discussed, the modelling also is arranged in a modularised way. The main modules presented in Chapter 5 are assisted by auxiliary modules (Appendix G) responsible for minor checks, calculations and output handling. As the research evolved, such modularised arrangement proved itself useful allowing the implementation of new features as the concepts were being discussed with the users (industry, satellite operators). Although this encompasses the development side of the framework and not its simple use, such characteristic is a powerful feature allowing the future developments of the framework as a tool assisting new types of OOS.

As identified through the different discussions and iterations with industry and operators, some attributes used to access value for their systems will be of limited access or proprietary information. The method selected for the modelling can also allow this information to be included (by the use of a user specific module) without having to share such information with other parties. A more simplified option, however, has been discussed in Chapter 5, specifically regarding User Defined Functions (UDF). Those could be used for to assist or complement the metrics used currently but could also dictate changes in the environment the satellites operate. Highlighted by Case 4 in Chapter 7, changes in the market after a given time could be included using a function changing over time, for example, TTBE and Discount Rate.

The choice for Excel VBA for modelling helps the framework to stay close to what the users would have on hand when exploring cases of servicing. Additionally, it opens links for the inclusion of this modelling in a more comprehensive environment, may the user find it necessary. This also results in not being a computing-intensive tool, not demanding additional packages or specific requirements that may conflict with the users' views. Being a flexible modelling and simulation environment, Excel VBA also offers potential links with other platforms the user may require considering (e.g. Matlab, STK). Once more, the modularised structure of the modelling allows this link without major disruption of the baseline model.

Agent Base Modelling and Simulation fits to the main suggested purpose to model the operation and interaction of agents (Servicer and Client). Being the main modelling structure defined, ABMS could be improved with characteristics of Discrete Event

Simulation (DES) or other desired operational modelling techniques. This is already partially modelled with the different options for failure simulation, either user defined or stochastic.

The modelling of the framework lay grounds for more complex analysis in OOS toward optimisation. Chapter 5, followed by Use Case 2 of Chapter 7, show the solution exploration feature which is not observed elsewhere in the literature. With the capability of the framework to generate a set of results for a given range of different variables, the inclusion of optimisation (or pre-optimisation) techniques can push even more its capabilities. Some of this pre-optimisation methods were demonstrated in the previous chapters, indicating how a more attractive condition for servicing could be found by using the solution exploration for the entire fleet, or even, for a Client individually.

From a modelling perspective, the main routine established for the framework could be looped consecutive times, storing the information about each run, to be used later to iterate the main inputs for Client and Servicer operation.

8.3 Simulation

The framework has been able to simulate a variety of applications of servicing, focusing on the most commercially appealing cases to be demonstrated in the next 5 years. From the results generated with the demonstration of the framework and the use cases, some aspects observed in the current OOS trend can be replicated/identified.

The reduced flexibility of *Lifetime Extension* cases, mainly limited by the resources and constrained by the costs of Client and Servicer, is one of the points highlighted in the presented results. Analysing the evolution of the proposed concepts for *Lifetime Extension* (MEV mainly [140]), it is possible to notice the incremental change of the system, suggesting a more multi-operation approach to bring more flexibility for the Servicer operator. MEV, initially proposed as a single dedicated system for *Lifetime Extension* applications now is portraited with additional features such as “propulsion packs” [174] to be installed on Client satellites. In this way, the same pushing/tugging services could be provided to its main/prime Clients, while other Clients are covered by the use of “propulsive packs” (consequentially generating more income). This also bypass one of the main characteristics of *Lifetime Extension* as indicated by the results; the time dedicated to one Client and considerable small fraction of idle time.

Although the demonstration of this specific case as a multi-application case (Use Case 4 from Chapter 7) would be equally relevant to the current OOS scenario, it would replicate some of the final results already explored in previous cases of this thesis the extension of lifetime. Therefore, the case of MEV as a multi-application servicing is also possible to be simulated in the framework, although not demonstrated herein.

Another Servicer dedicated to *Lifetime Extension*, currently indicated as a single application system, is the SpaceDrone-1 from Effective Space Solutions [135]. In this system, the Servicer is relatively less massive than other proposed Servicers, which also helps to improve the flexibility for this application. This is also observed in the simulations when considering Servicers with lower mass (and cost).

From the results it is possible to note that, even if a correlation of a specific variable (e.g. t_{life}, cost) is observed with a final result (profit cases and scheduling), the presence of other agents (Client or Servicer) play a major role. In this way, the simulation and analysis of how "stable" a case can be are likely to be majorly representative to that specific simulation case. This bring the necessity for such framework to allow the user to explore in detail each specific case, avoiding taking generalised pre-assumptions regarding to servicing that might be relevant or beneficial to a particular scenario.

Regarding specific points overlapping the simulation and modelling, some of the features included are still at the early stages due to the lack of contents available in the literature, mainly focused on commercial uses of OOS.

For cases of *Maintenance and Repair*, the fuel depot is discussed in Chapter 6, and also simulated in the use cases of Chapter 7. At the current stage of the framework the depot is considered solely regarding its position in the orbital slot. No other assumptions are made at this stage regarding its design, commissioning and operation from the perspective of the "Depot Operator". However, as demonstrated by the results (chapters 5, 6 and 7), once a Servicer uses the depot for refuelling, it will pay for the amount of propellant transferred. For simplification, the price per kg of propellant in this case is assumed to be the same as the Servicer charges the Client for refuelling. However, a more refined approach would lead to the exploration of more complex scenarios of servicing where the fuel depot can be considered as an additional agent of the simulation with its own characteristics and requirements.

Another point touching the *Maintenance and Repair* cases regards to the refuelling of Clients using electric propulsion. From the modelling and simulation perspective, the Servicers for refuelling considered in the framework can be used for this task. In demonstration considered herein, however, it was assumed the refuelling of propellant for electric propulsion is not available. It has been discussed about how difficult it could be to perform such task since some of these tanks could be provided loaded and sealed, ready for integration with the satellite. Discussions undertaken throughout the research with experts in satellite operator companies identified concerns with this technology (e.g. Xenon refuel). In practical terms, the simulation can take this option as a demonstration for the Servicer or Client decision, but such results would need to be presented with a more extensive discussion on the applicability and examples of actual systems.

Focused on the usability and presenting the information of a simulation, the dashboard provided by the framework assists in the decision making and quick analysis of servicing cases. This is particularly important in environments such as Concurrent Design/Engineering meetings where multiple decisions and options are checked in a short period of time.

The simulation time can be checked also looking to the time spent in the simulations (either a single simulation or a Solution Exploration), which shows its usability and compatibility to the same type of concurrent meetings. Single simulations would be the main focus of such meetings, with simulations taking around minutes to be completed and discussed. Although also suitable for Concurrent Design meetings (depending on the parameters used), Solution Exploration could take longer to be completed, being more suitable for pre or post meeting environments.

The addition of other metrics can be represented in the main dashboard as well as specific information about Client and Servicer timelines, if necessary. Lastly, if the user needs to analyse one specific metric of a given satellite, those are all provided as secondary results as included in the different chapters of this thesis.

The framework is designed to consider the concurrent relation of Client and Servicer. However, in a non-concurrent scenario the framework is also applicable. The main characteristic driving the concurrency in OOS at the current stage is the compatibility between Client and Servicer. In a future scenario where OOS is fully implemented in space missions (or at least in most space missions), this compatibility would be assured from the conception phases.

In this case, for example, the framework can be used by a Servicer operator to explore a wider option of Clients, encompassing, virtually, all the satellites in orbit to find those more suitable to a servicing condition. In parallel, a Client operator would be able to explore a range of well-established Servicer operators offering different options of servicing at different conditions.

This non-concurrent use of the framework would then be solely focused on the operation side, eliminating the necessity of analysing the effect of servicing adoption early in the design. This would reflect a more responsive use of the framework for decision-making at a short notice.

8.4 Limitations of the Tool and Research

This section covers general limitations of the framework and the research, pointing to their consequences and potential ways to bypass or improvement.

As discussed before, the consideration of the fuel depot in the framework assumes a given position where the Servicers move when a replenishment condition is reached. This is a current limitation which could be explored in future cases, main an additional agent be included (Section 8.5.4).

Due to the constraint of Excel VBA, the results of one simulation can only be shown up to 256 satellites, even though a larger number of Client satellites can be simulated at once. Simulating a larger number of Clients will result in a crash of the code in the final modules of output handling. Although such condition will be unlikely to be necessary, different visualisation methods could be used or a different output handling strategy if that is the case.

Also mentioned in Chapter 5, the type of propulsion used are considered as a single one for each phase (insertion and station keeping). However, current satellites can also use multiple types of propulsion for a given phase (e.g. bi-propellant and electric propulsion for station keeping). This limitation is mainly due to the lack of enough information available in the database.

Still regarding the propulsion of satellite, the mixture ratio is a current limitation. Different mixture ratios can be used specially when considering, for example, bi-propellant for orbit raising and mono-propellant for station keeping. However, similar to the previous point, since this information could not be easily found the framework considers this as a standard input (50/50). At the moment, a bypass for the representation of a mixture ratio different from the 50/50 would be the definition of the propulsion type for each phase (for example bi-prop for orbit raising and mono-prop for station keeping). Such limitation could be later reduced with the option for the user define more specifically their preferences for mixture ratio.

The ΔV estimation for electric propulsion is also limited by the assumption discussed in Chapter 5. For the range of ISP considered as standard in the framework for electric propulsion, the assumption is compatible. However, may higher ISP/low thrust types of propulsion be considered the indicated references should be used as main guidelines for a direct definition of the ΔV capacity of the satellite.

About the consideration Client failures, two methods are used; failures defined by the user, with a given capacity loss at a given time of the operation, and failures based on a random generator. However, neither of the methods use direct inputs from the *Reliability* metric.

This limitation is due to the characterization of the satellite *Reliability* as a whole. The link of *Reliability* to the generation of failures in the simulation would require a dedicated module to relate the different *Reliability* values of each subsystem, which could then be used to estimate a potential failure. In addition to a more refined method for failure estimation and generation, the use of *Reliability* of each subsystem could then help to analyse the effects of installing new subsystems in the Client satellite, e.g. Payload Augmentation.

8.5 Further work

Considering that OOS is currently becoming more popular in the industry, the potential applications and refinement of the framework are likely to be relevant for the future users.

The following points are immediate characteristics to be included in the framework or analysis to be explored. However, as certain types of servicing become more popular or attractive and as more operators get interested in OOS, other developments in the framework might appear.

8.5.1 Optimisation methods

As discussed before, the solution exploration feature opens the opportunity for a series of optimisation methods to be applied.

Those could be focused on finding optimum conditions for servicing, either from an individual side or considering optimum for Servicer and Client. Once more, the consideration of the different metrics is also a powerful attribute of the framework that could be explored in an optimisation routine. From a modelling aspect, the simplified loop of conditions for a simulation with a single storage of the results/information are expected to work an overall option for the optimisation. However, as more advanced methods of optimisation (e.g. genetic algorithms), the capability of information exchange with other suites (e.g. Matlab) could be explored to improve the overall operability.

Different research in the literature focuses on trajectory optimisation techniques which could be incorporated into the framework. This have potential bring a well explored area of research together with the systemic view of Servicer and Client, and their different evaluation metrics as characterised in the framework.

Still linked to the optimisation area, the decision methods to change a parameter in the search of an optimal condition can be used, in a simplified form, for the decision of the agents under a certain state and condition. For example, a Servicer decision to service one Client instead of a different one, or even an automated decision to which type of application a Client operator should choose. As discussed in the previous chapter, the concurrent characteristic of this framework and the simulations performed can be sensitive to automate decisions, therefore an incremental implementation of such attributes is suggested.

8.5.2 User defined functions and databases

The possibility of a more tailor-made consideration of the user requirements or views is another attribute for future work in the framework.

Although not expected to be heavily demanding from a modelling perspective, the link of the framework with different databases represent a potential extensive work. As operators might have their own databases and heritage in their design and procurement, the capability of allowing the framework to consider it in the simulations could bring more insightful outputs.

Such attribute would represent more flexibility for the user and the framework as other metrics could be analysed without major changes in the model structure or modules. Additionally, this could represent more privacy may the user want not to disclose specific information (e.g. financial, costs, operation).

8.5.3 Orbital manoeuvres

Although the main current developments for OOS focuses on GEO operators, there is the potential for servicing operations in LEO and MEO.

Technically, the main equations used for the calculation of phasing manoeuvres could still be used as an initial assessment. However, a proper consideration of position and velocity brings more fidelity to the results. Additionally, the consideration of more complex manoeuvres such as large changes in inclination, LEO to GEO transfers will help to characterise other proposed types of servicing.

Another point of great relevance for the application of the framework would be for ADR, either from a sustainability of profitability points of view. As mentioned, the current structure of the framework and its equations for phasing would have to start with the assumption of a “static” snapshot of the Servicer and potential debris. In this way the Servicer would manoeuvre to the expected position of the debris. However, such assumption also forces the consideration that both Servicer and debris are in the exact same orbit. For a more representative characterisation of this environment, a more comprehensive mathematic model for orbit propagation would be beneficial, specifically for LEO cases.

For Servicers operation in the GEO ring, further work could explore the operation in a constantly drifting base. Such condition could then allow better opportunities to manoeuvre to Client locations, with potential savings on propellant and time. A similar assumption could be made, also considering the refuelling base in a constant drift. This would allow the user to explore more detailed characteristic of the logistics enabled by this assumption.

8.5.4 Resources logistics

Linked to the previous points mentioned, the consideration of the logistics of launching and allocating resources is another point that could be improved in the framework in a future work.

As more insight of servicing applications and systems become available, the framework could be improved. Such improvements would be to allow the framework to account, for example, for the launch (and potential delays) of resources, the supply chain for depots and Servicers, the use of Servicers in different orbits (slightly lower orbits) to allow a quicker re-visiting time. The work included in COSEMS [148] could be used as a starting point, although a more renewed view of the user requirements would be relevant for the current scenario of OOS.

A simplified first step towards a more representative logistics model would be the inclusion of additional modules to dictate the rate a given resource (e.g. propellant, subsystems) reaches the orbit. Additionally, the inclusion of another agent in the model (e.g. Provider) opens more possibilities for the framework to be used in the current and future scenario of commercial servicing. Herein, the inclusion of the decision models is also relevant with potential benefits.

8.6 Conclusions

The main objectives proposed in this thesis have been completely achieved:

Objective 1: To identify the On-Orbit Servicing (OOS) capabilities and the influence of OOS on the lifecycle of a Client spacecraft and operation of a Servicer spacecraft.

The identification of OOS capabilities and influence over design and operation indicated that the lack of understanding of Client-Servicer relationship is the main systemic reason why OOS is not fully implemented in the current decision process of space systems. This was possible due to the systemic analysis of technological and implementing issues observed in the literature and previous developments.

The variety of concepts, definitions and applications needed to be put into a unified perspective to allow a global view of the challenges and potential benefits of OOS. Such perspective was achieved via the proposed taxonomy and main functional decomposition starting from the Servicer side. This then allowed to draw the proper links with the Client side in order to outline the systemic relation between Servicer and Client.

As a main finding, at the current stage of OOS developments, operators looking to take advantage of more advanced types of servicing (e.g. repurpose or assembly) would necessarily need to undertake major rearrangements in the design process. Such rearrangements would be mainly linked to the close cooperation with the Servicer side, potentially resulting in a “one of a kind” final product. On the other hand, less complex types of servicing such as life extension will have a major decision point in late phases of the design, potentially going to the operation phases. Servicing applications between these two levels of complexity (e.g. upgrades/payload augmentation) will depend most on the outlining of the subsystems to be installed, therefore demanding more attention at early to mid-phases of the design.

Objective 2: To establish and operate the framework capable to incorporate TRL, business models and user needs to simulate the interaction of Servicer and Client.

Simulation of the interaction between Client and Servicer was achieved by the establishment of the framework discussed in this thesis. The mathematical modelling using Agent Based Modelling and Simulation allowed the incorporation of the main findings from the first objective as characterisation parameters for the agents of the simulation. Such characterisation was also complemented by evaluation metrics to allow a broader use of the framework for different users, operators and servicing scenarios. The framework implementation based on a commonly used environment of systems and concurrent engineering reinforced its applicability for real case scenarios, at different phases of design and operation of space systems.

Important findings can be highlighted by the concurrency of the agents (Client and Servicer) in the actual adoption of servicing solutions by the Client, and its execution by the Servicer. Characteristics of how the Servicer spends its designed life will impact directly on the result of the servicing tasks on the Clients. Still regarding the concurrency of the agents, the results of the cases using the framework suggests the potential expansion of a servicing “eco-system”, similar to services provided on Earth for every-day facilities such as in the automotive industry. The different types of servicing explored in the use cases for the demonstration of the framework highlighted that cases of *Lifetime Extension* can represent a more challenging choice for the Servicer operator. Observing the proposition of the current OOS systems and their evolution since being publicly announced, some of this “lack of flexibility” can be used to explain a leaning towards a multi-servicing application.

With all the objectives met and the main identified gap in the knowledge addressed by the established framework, the future application of such a tool can be highlighted as a contribution. The growing scenario for OOS as identified in the first objective, expands the option to apply and expand the framework, both as an overall tool or a user-specific tool.

8.7 Summary of contributions

The present work has been able to fill the knowledge gap identified for the implementation of OOS in current and future space systems. As a summary of contributions, the following points can be highlighted:

- The development of a framework established the link between the two sides of OOS, successfully implementing and demonstrating its operation, behaviour, applicability and guidelines of use.
- The extensive available information from academic and industrial parts have been used to allow such framework to act as a tool to link Servicer and Client at early stages of development of a space system.
- The framework represents another resource to be used mainly by systems and concurrent engineers to translate the user needs and explore potential servicing cases. Being specifically implemented with OOS in mind, it highlights a capability not observed in the current research.
- The characterisation of Client and Servicer as a multi-metrics system to allow the consideration of OOS and use of the framework by different profiles of users.
- Features such as concurrent consideration of multiple agents (Clients and Servicers), their competing characteristics and capability of quick simulation are points not observed in the current research of On-Orbit Servicing.

As demonstrated through the work, the current trends towards servicing and near-future implementation highlights the relevance of the framework developed in this work and the impact of the contributions for current and future real-life developments.

Overall, the framework developed in this research allows interested parties to consider OOS scenarios and their potential benefits.

These novel contributions have been presented in journal paper publications.

Journal Papers:

- **Establishing a framework to explore the Servicer-Client relationship in On-Orbit Servicing** – Matos de Carvalho, T.H., Kingston, J., *Acta Astronautica* (ISSN 0094-5765), https://doi.org/10.1016/j.actaastro.2018.10.040
- **Modelling the Concurrent Relation of Client and Servicer in On-Orbit Servicing** – Matos de Carvalho, T.H., Kingston, J., *Concurrent Engineering: Research and Applications* (ISSN 1063-293X) (Under Review)

Conference Papers:

- **On-Orbit Servicing Readiness Assessment: The Servicer Perspective** – T. Matos de Carvalho, J. Kingston, in: *Proc. 67th International Astronautical Congress*, 2016: p. 10 (IAC-16,D1,7,4,x33179).
- **Simulating the Servicer/Client Relationship in On-Orbit Servicing Scenarios** – T. Matos de Carvalho, J. Kingston, in: *Proc. 68th International Astronautical Congress.*, 2017: p. 12 (IAC-17,D1,6,6,x41177).

Co-authored publications[16]*:

- ***Journal Paper*: Technology roadmap for a magnetically confined fusion powered spacecraft** – D.A. Homfray, M. Gorley, C. Harrington, A. Hollingsworth, J. Morris, T. Matos de Carvalho, *JBIS – Journal of the British Interplanetary Society* (ISSN 0007-084X). (2017).
- ***Book Chapter*: Chapter 26: Space Waste** (Co-authored with Gene Stansbery and Dr. Stephen Hobbs) – *Waste: A Handbook for Management*, (ISBN 0123814758)

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[16] Publications addressing, among other subjects, the use of OOS and its importance for current issues and future developments of space systems.

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APPENDICES

This section covers the additional/complementing content used through the thesis chapters.

Appendix A – OOS Glossary

This glossary presents the recurrent terms used in this thesis with the main definition found in the literature and/or the meaning within the context of this research. For the definition coming from the literature, the text is presented as is (indicated by quotes and italic), including the reference number.

Application – Different categories of servicing (Table 2-2).

Client – System/satellite being serviced or assembled by the Servicer.

Function – Specific action/task to accomplish the objective of a system/mission. "*Intended effect of a product.*" [175]

Functional Decomposition – "*A sub function under logical decomposition and design solution definition, it is the examination of a function to identify sub functions necessary for the accomplishment of that function and functional relationships and interfaces.*" [143]

Heritage – "*Refers to the original manufacturer's level of quality and reliability that is built into the parts which have been proven by (1) time in service, (2) number of units in service, (3) mean time between failure performance, and (4) number of use cycles.*" [143]; "*Property that is or may be inherited; an inheritance*" [Oxford Dictionary]

Hosted Payload – *"A hosted payload is a portion of a satellite, such as a sensor, instrument or a set of communications transponders that are owned by an organization or agency other than the primary satellite operator."* [31] *"… refers to the utilization of* *available power, mass and space on commercial satellites to accommodate additional transponders, instruments or other space-bound items."* [29]

Metric – "*The result of a measurement taken over a period of time that communicates vital information about the status or performance of a system, process, or activity.*" [143]

On-Orbit Servicing – Inspection, maintenance, upgrade, repair, refuel and assembly of a system in space by a secondary system performing such tasks.

Operator – Entity/people/organisation in control or operation of either Client or Servicer.

Persistent Platform – Satellite system with modularised architecture, with its main primary subsystems lasting for a longer time and subsystems such as payload replaced through the operational life.

Reliability – "*The measure of the degree to which a system ensures mission success by functioning properly over its intended life. It has a low and acceptable probability of failure, achieved through simplicity, proper design, and proper application of reliable parts and materials. In addition to long life, a reliable system is robust and fault tolerant.*" [143]; "*The ability of an item to perform a required function under given conditions for a given time interval.*" [175]; "*It is generally assumed that the item is in a state to perform this required function at the beginning of the time interval.*" [175]; "*Generally, reliability performance is quantified using appropriate measures. In some applications these measures include an expression of reliability performance as a probability, which is also called reliability*." [175]

Servicer – System/satellite responsible to execute tasks from each servicing application.

Technology Assessment – "*A systematic process that ascertains the need to develop or infuse technological advances into a system. The technology assessment process makes use of basic systems engineering principles and processes within the framework of the PBS. It is a two-step process comprised of (1) the determination of the current technological maturity in terms of technology readiness levels and (2) the determination* *of the difficulty associated with moving a technology from one TRL to the next through the use of the AD2.*" [143]

Technology Readiness Level (TRL) – "*Numerical scale used to express the degree of which any particular technology is ready for application in operational mission.*" [63]

Utility – "*A measure of the relative value gained from an alternative. The theoretical unit of measurement for utility is the util.*" [143]. The flow of service that a system is forecast to deliver over time (per unit of time), as presented by Saleh [164].

Appendix B – Definitions Equivalence

Table B-1 – OOS definitions equivalence

Ref.	Definitions	Applications equivalence						
		DO	RO	LE	RR	MR	RP	AS
NASA [3]	Relocation	-	X	-	-	-	-	-
	Mechanical assist	-	-	-	X	-	-	-
	Repair/upgrade	-	-	-	-	X	-	-
	Resource replenishment	-	-	-	-	X	-	-
	On-orbit assembly	-	-	-	-	-	-	X
	Refurbishment/Refuelling	-	-	-	-	X	-	-
	Construction	-	-	-	-	-	-	X
	Debris Removal	X	-	-	-	-	-	-
Waltz [4]	Assembly	-	-	-	-	-	-	X
	Orbit Transfer	X	X	-	-	-	-	-
	Re-supply	-	-	-	-	X	X	-
	Maintenance	-	-	-	-	X	-	-
	Special	-	-	-	X	-	X	-
Sommer, Kreisel, Ellery [5] [6] [7] [8]	Re-Orbiting	-	X	-	-	-	-	-
	De-Orbiting	X	-	-	-	-	-	-
	Salvage	-	-	-	-	-	X	-
	Maintenance	-	-	-	-	X	-	-
	Repair	-	-	-	-	X	-	-
	Retrofit	-	-	-	-	X	X	-
	Docked Inspection	X	X	X	X	X	X	X
	Remote Inspection	X	X	X	X	X	X	X
Sullivan [44]	Orbit correction	-	-	-	X	-	-	-
	Deployment assistance	-	-	-	X	-	-	-
	Component repair	-	-	-	-	X	-	-
	Consumables resupply	-	-	-	-	X	-	-
	Removal (Satellites, Debris)	X	X	-	-	-	-	-
	Relocation	-	-	-	X	-	-	-
	Consumables resupply	-	-	-	-	X	-	-
	Component replacement	-	-	-	-	X	X	-
	Inspection	X	X	X	X	X	X	X
	Assembly	-	-	-	-	-	-	X
	Scavenging	-	-	-	-	-	X	-
Richards [153]	Inspect	X	X	X	X	X	X	X
	Relocate	X	X	X	X	-	-	-
	Restore	-	-	-	X	-	-	-
	Augment	-	-	-	-	X	-	-
	Assemble	-	-	-	-	-	-	X
Visentin [176]	Inspection	X	X	X	X	X	X	X
	Mechanical assist	-	-	-	X	-	-	-
	EOL Re-orbiting	-	X	-	-	-	-	-
Benedict [177][139]	Robotic Manipulations	-	-	-	X	-	-	-
	Life Extension	-	-	X	-	-	-	-
	Towing	X	X	-	-	-	-	-
	Inspections	X	X	X	X	X	X	X
Xu [125]	Re-orbiting	-	X	-	-	-	-	-
	Inspection	X	X	X	X	X	X	X
	Repair	-	-	-	-	X	-	-
	Life Extension	-	-	X	-	-	-	-
	Orbit Inserting	-	-	-	X	-	-	-
Graham [28]	Refuelling	-	-	-	-	X	-	-
	Life Extension	-	-	X	-	-	-	-
	Array Operations	-	-	-	X	-	-	-
	Mechanical Intervention	-	-	-	X	-	-	-
Arantes [178]	Refuelling	-	-	-	-	X	-	-
	Repair and replacement	-	-	-	-	X	-	-
	Reboost	-	-	X	-	-	-	-
	De-Orbiting	X	-	-	-	-	-	-
ISU [99,119]	Debris Removal	X	X	-	-	-	-	-
	Docked Inspection	X	X	X	X	X	X	X
	Maintenance	-	-	-	-	X	-	-
	Payload Delivery	-	-	-	-	-	X	-
	Remote Inspection	X	X	X	X	X	X	X
	Repair	-	-	-	-	X	-	-
	Retrofit	-	-	-	-	X	X	-
	Salvage	X	-	-	-	-	-	-
	Spacecraft Recovery	-	-	-	X	-	-	-

DO: De-orbiting, RO: Re-orbiting, LE: Lifetime extension, RR: Rescue and recover, MR: Maintenance and repair, RP: Repurpose, AS: Assembly

Appendix C – OOS Systems and Subsystems

The content of this section was generated at the initial phases of the research. The main objective was to summarise the available information for systems and subsystems aimed at OOS. Although a simplified view of it was presented in Table 3-3, Table 3-4, and Chapter 3, it is useful to present the main source/method used.

A set of 4 simplified questions were defined to capture, when available, the information about each concept. This was used later to outline the main functions of each concept as discussed in Chapter 3.

Therefore, some of the information presented for the system and subsystems are in its original form/writing (indicated by quotes and italic), from the main reference/source indicated.

C.1 Search Questions

1. What is it?
2. Status? (concept / development / operation)
3. What and how have been done (supposed to do)?
4. When and where have been done (supposed to do)?

C.2 Systems and Subsystems Summary

ORS – Orbital Refuelling System [4]

1. Fluid Transfer Testbed

2. Operation (Phase E)

3. "*The Orbital Refueling System (ORS) experiment on the Shuttle STS-41G mission in 1984 demonstrated the ability to refuel satellites in space. Following an Extravehicular Activity (EVA) to attach a flexible propellant line to a typical satellite valve in the payload hardware, six transfers of hydrazine between two diaphragm tanks were successfully conducted*."

4. 1984 (STS 41-G)

ROTEX – RObot Technology EXperiment [88]

1. Multisensory robot

2. Operation (Phase E)

3. "*Tasks pre-programmed and reprogrammed from ground), remotely controlled (tele-operated) by the astronauts, remotely controlled from ground via the human operator as well as via machine intelligence.*"

   a) assembling a mechanical truss structure from three identical cube-link parts
   b) connecting/disconnecting an electrical plug (orbit-replaceable-unit-ORU-exchange using a "bayonet closure")

   c) grasping a floating object
4. 1993 (Spacelab D2/Shuttle)

ESS – Experimental Servicing Satellite [89]
1. Servicing spacecraft
2. Concept (ESS, Phase 0/A*)
> *"The satellite is now sufficiently defined to allow component procurement (in the next stage of the project) to proceed."*

3. Servicing a non-cooperative target in GEO. Acquisition, inspection and servicing, re-orbit (graveyard)
   a) rendezvous
   b) capture: capturing/manipulator tool/image processing
   c) servicing: manipulator + exchangeable tool adaptors
4. 1994 (Feasibility study), TVSat-1

ESS-T [90]
1. Manipulator robot (ESS lab mockup)
2. Operation (Phase E)
3. Tele-presence and tele-operation
> *"ESS technologies as prepared at DLR include the experimental lab mock-up for simulating dynamic interactions between robot and satellite by implying two industrial robot systems"* [90]

   a) capture: capturing/manipulator tool/image processing.
4. 1995 (DLR – Ground lab)

ESS-OSS [98]
1. Servicing spacecraft
2. Concept (ESS-OSS, Phase 0)
3. Capture and de-orbit of a specific target (ROSAT)
4. 1999 (De-Orbiting Study)

Ranger TFX – Ranger Telerobotic Flight Experiment [91]
1. Manipulator robot
2. Concept (ESS, A)
3. Tele-presence and tele-operation
> *Two Ranger vehicles are being built. The first, designed to operate under water, will undergo extensive testing at the Neutral Buoyancy Research Facility on the University of Maryland campus to get basic data on its operation and capabilities. The second, as nearly identical to the first as possible, is a flight vehicle, scheduled for launch in late 1996.*
>
> *The project will correlate neutral buoyancy robotic simulation by nearly identical underwater and flight units performing identical tasks in both environments; that will increase understanding of the capabilities and limitations of existing techniques for simulating the space environment on Earth.*
>
> *On orbit, Ranger will demonstrate a variety of space operations tasks, from the relatively simple installation of Orbital Replacement Unit modules to complex satellite servicing/refueling tasks that have thus far only been performed by astronauts in extravehicular gear. Utilizing telepresence ground-based control, coordinated manipulation operations, automated rendezvous and docking technology and a hybrid propulsion system, Ranger will conduct simulated satellite servicing exercises to characterize the operational capabilities of free flying robotic systems.*
>
> *Ranger represents the first of a new class of low-cost expendable robots designed for research and servicing in areas beyond the reach of the Space Shuttle. The Ranger vehicles will incorporate design considerations for advancing technical education in the U.S. by encouraging direct student involvement in space research.*

4. N.A.

GSV – Geostationary Service Vehicle [92] [94]
1. Servicing spacecraft
2. Development (Phase B*)
> *"Following these positive initial results, the agency issued a competitive request for proposals to industry to conduct a more detailed study of the GSV mission requirements and to perform a preliminary design of such a servicing satellite. ...a contract was awarded to DASA (Daimler-*

Benz Aerospace) as a prime contractor…" "Since the first publication of the GSV concept in 1989, assessments in applications and technical requirements have been extensively studied, hand-in-hand, at two opposite sides of the Earth."

3. Servicing a failed satellite. Target search, acquisition, rendezvous, inspection and servicing, re-orbit (orbit changes and graveyard)

   a) rendezvous
   b) capture: capturing/manipulator tool/image processing. *"reaching the repair zone; close inspection"* [94]
   c) telepresence: *"inspection of a satellite having a severe malfunction and where a close-up view of the satellite can be of help to clarify what went wrong. This diagnostic data can be a basis for recovery actions from ground."* [94]
   d) servicing: "*mechanical assistance to a satellite in trouble, for example a non-deployed solar array or antenna, to restore the situation. "intervention by tools, e.g.; removal / replacement of sections of thermal blanket; severing of restrain cables which prevent antenna/solar arrays deployment; hinging/extraction of stuck deployable mechanisms"* [94]
   e) *"end-of-life re-orbiting of uncontrolled satellites into a graveyard orbit, an operation which will become more and more important to maintain commercial exploitation potentials of GEO."* [94]

4. 1996 (detailed study)

ETS-VII – Engineering Test Satellite 7 [95] [96]

1. Servicing spacecraft + target spacecraft
2. Operation (Phase E)
3. Rendezvous and docking, robotic operations [96]
   a) rendezvous and capture: capturing/manipulator tool/image processing, autonomous and tele-operation
   b) parts manipulations, propellant replenishment
4. 1997 (Chaser/Target)

Aestos [99]

1. Servicing spacecraft
2. Concept (Phase A)
3. "*A space tug called "Aetos". This will be capable of navigating to the target satellite, grappling it, interfacing with its fuel system, returning it to the ISS, interfacing with the ISS and returning the satellite to its original orbit."*
4. N.A.

ATLAS – Advanced Telerobotic Actuation System [100]

1. Servicing spacecraft
2. Concept (Phase A* [100])
3. N.A.
4. 1996/2000 (Concept)

X-MIR-Inspector [97]

1. Servicing spacecraft
2. Operation (Phase E)
3. Tele-presence and tele-operation
4. 1997

SUMO – Spacecraft for the Universal Modification of Orbits [102] [8]

1. Servicing spacecraft
2. Concept (Phase 0)
3. Service "uncooperative" satellites.
   "SUMO is designed to service many types of customer spacecraft without requiring servicing aids such as grapple fixtures and retroreflectors to be installed on the customer spacecraft; however it can take advantage of such aids if they exist."
4. 2002 [8]

SUMO (Testbed) – Spacecraft for the Universal Modification of Orbits [113]

1. Multisensory robot (spacecraft testbed)
2. Operation (Phase E)
3. Rendezvous and docking, robotic operations.
   "Operations Testbed was the primary test facility for the SUMO laboratory demonstrations. This facility represents a dual-platform spacecraft motion simulator that provides a realistic test environment for verification of sensor and control technologies. The facility consists of two independent 6 degree-of-freedom platforms,

a local-area network architecture for real-time ground-to-platform and platform-to-ground communications, and software to emulate spacecraft mass properties, thruster and reaction wheel actuators, and on-orbit environmental disturbances."

a) rendezvous and capture: capturing/manipulator tool/image processing, autonomous and tele-operation
b) parts manipulations, propellant replenishment

4. 2005

FREND – Front-End Robotics Enabling Near-Term Demonstration [114]

1. Manipulator robot
2. Operation (Phase E)

"The DARPA-sponsored FREND program was created to prove the capability of autonomously executing an unaided grapple of a spacecraft which was never designed to be serviced. In successfully demonstrating this capability in the Navy Research Laboratory's Proximity Operations Test Facility, it addressed one of the few remaining obstacles to practical robotic servicing of spacecraft on orbit."

3. Proximity operations, robotic operations
   a) capture: capturing/manipulator tool/image processing, positional accuracy, rigid connection
   b) manipulations: dexterity, end-effector
4. 2006/7(NRL)

ROGER – RObotic GEostationary Orbit Restorer [103] [104]

1. Servicer spacecraft
2. Concept (Phase A)
3. Servicing a non-cooperative target in GEO. Acquisition, inspection and servicing, re-orbit (graveyard)
   a) rendezvous
   b) capture: capturing/image processing
   c) servicing: manoeuvring, re-orbit
4. 2003

XSS-10 [105]

1. Servicing spacecraft
2. Operation (Phase E)
3. "*Acquisition and inspection: semi-autonomous relative navigation, manoeuvre, target tracking and real-time communication technologies"*
   a) Rendezvous
   b) Proximity operations: image processing
   c) Servicing: inspection/manoeuvring
4. 2003 (Delta 2nd stage)

XSS-11 [109]

1. Servicing spacecraft
2. Operation (Phase E)
3. Acquisition and inspection: semi-autonomous relative navigation, manoeuvre, target tracking and real-time communication technologies
   a) Rendezvous
   b) Proximity operations: image processing
   c) Servicing: inspection/manoeuvring
4. 2005

DART – Demonstration of Autonomous Rendezvous Technology [110] [111]

1. Servicing spacecraft
2. Operation (Phase E)
3. Autonomous rendezvous capabilities, acquisition and inspection
4. 2005

ROKVISS – Robotic Component Verification on ISS [18] [112]

1. Robotic manipulator
2. Operation (Phase E)
3. Tele-presence and tele-operation

"The ROKVISS experiment consists of a small two-joint robot mounted on a Universal Workplate (UWP), a controller, an illumination system, a power supply, and a mechanical contour device for verifying the robot's functions and performance." [112]

a) "qualification of DLR's highly integrated, light weight robotic joint-elements for their future application in free space environment"
b) "demonstration of the so-called Tele-Presence Operational Mode under real

mission conditions, i.e. the operator is directly involved into the control loop via force-reflecting tele-manipulation and up-and down-link round trip time of less than 500 ms"

4. 2005

<u>CX-OLEV – ConeXpress Orbital Life Extension Vehicle</u> [106] [107] [108]

1. Servicing spacecraft
2. Development (Phase B) [107] [108]
   "The phase B1 as executed during 2004 has been successfully closed with a baseline review by ESA and Orbital Recovery Ltd. Feasibility of CX-OLEV and the mission has been demonstrated and a baseline design has been established as well as the programmatic for the implementation phase. The first part of this implementation phase, a B2 phase ending with a Preliminary Design Review is envisaged to start April 2005."
3. Lifetime extension:
   "CX-OLEV intercepts the Client's satellite in geostationary orbit, docks with it, and takes over its attitude and orbit control function. This is a seamless service which allows the Client to continue offering his communications services without interruption"
   a) Rendezvous
   b) Proximity operations: image processing and docking
   c) Servicing: inspection/manoeuvring
4. 2004

<u>TECSAS – TEChnology SAtellite for demonstration and verification of Space systems</u> [112] [116]

1. Servicing spacecraft
2. Concept (Phase A)
3. Acquisition, inspection, capture and control,
   "*The TECSAS project aims at the in-orbit qualification of the key robotics elements (both hardware and software) for an advanced space servicing system, especially with respect to docking and robot-based capturing procedures." "... far rendezvous, close approach, inspection fly around, formation flight, capture, stabilization and calibration of the compound, compound flight manoeuvre, manipulation of the target, active ground control via telepresence, passive ground control during autonomous operations (monitoring) and controlled de-orbiting of the compound."* [112]
4. 2006 (programmatic reorientation) [116]

<u>DEOS – Deutsche Orbitale Servicing Mission</u> [116]

1. Servicing spacecraft
2. Development (Phase B)
3. Capturing a non-cooperative target. Acquisition, inspection and servicing, de-orbit, re-orbit (graveyard)
   "DEOS will focus on Guidance and Navigation, capturing of non-cooperative as well as cooperative client satellites, performing orbital manoeuvres with the coupled system and the controlled de-orbiting of the two coupled satellites" [116]
4. 2010 (ongoing)

<u>SMART-OLEV – SMART Orbital Life Extension Vehicle</u> [117]

1. Servicing spacecraft
2. Development (Phase B*) (based on the previous development of the CX-OLEV [179]) *Reasonable to consider Phase B given that the basic functions are adapted from CX-OLEV and the BUS originated from an operational concept (SMART-1)
3. Lifetime extension:
   a) Rendezvous
   b) Proximity operations: image processing and docking
   c) Servicing: inspection/manoeuvring
4. 2007/8

<u>Orbital Express</u> [11] [118]

1. Servicing spacecraft (servicer + target)
2. Operation (Phase E)
3. General servicing tasks
   "This mission demonstrated short range and long range autonomous rendezvous, capture and berthing, on-orbit electronics upgrades, on-orbit refuelling, and autonomous fly-around visual inspection using a demonstration client satellite"
   "The Orbital Express program, envisioned and funded by the Defense Advanced

Research Projects Agency (DARPA) and Boeing, was designed to prove that satellite servicing was technically and economically feasible through development is a standard satellite servicing architecture for a future operational system, and demonstration of the readiness of various technologies required for autonomous satellite servicing"

- *a) Non-proprietary servicing interfaces*
- *b) Autonomous operations and servicing software*
- *c) Autonomous proximity operations and Autonomous Guidance Navigation & Control (AGN&C); Autonomous capture and mating*
- *d) ORU transfer*
- *e) Zero gravity fluid transfer*
- *f) Avoidance of contamination of NEXTSat;*
- *g) Advanced robotics*

4. 2007

ODORU – On-Demand Orbital Replacement Unit [119]
1. Servicing spacecraft
2. Concept (Phase 0)
3. ORU servicing / autonomous operations
   - a) Rendezvous
   - b) Proximity operations: image processing and docking
   - c) Servicing: inspection/manoeuvring/ORU replacements
4. 2007

SDMR [120]
1. Servicing spacecraft
2. Concept (Phase A*) (Prototype tests)
3. Active debris removal
   - a) *"Rendezvous with the debris object (target) and measure its motion."*
   - b) *"Fly around the target, and make a final approach to capture it."*
   - c) *"Capture the target using an extensible folder arm."*
   - d) *"Extend an EDT fixed at the root of the folder arm."*
   - e) *"Autonomous control of tether inclination."*
4. 2009

DR LEO – Debris Removal from Low Earth Orbit [123]
1. Servicing spacecraft
2. Concept (Phase A) [123]
3. Active debris removal (selected targets)
   - a) Rendezvous
   - b) Proximity operations: grappling/docking
   - c) Servicing: manoeuvring/de-orbit
4. 2010

RetroSpace/Sat [124] [40]
1. Servicing spacecraft
2. Concept (Phase A) [124]
3. Active debris removal
   - a) Rendezvous
   - b) Proximity operations: grappling/docking
   - c) Servicing: manoeuvring/de-orbit
4. 2010

Restore-G/L [3]
1. Servicing spacecraft
2. Concept (Phase B)
3. Active debris removal
4. 2010

GEOSS [125]
1. Servicer spacecraft
2. Concept (Phase 0)
3. Universal servicing
4. 2011

ARGON [127] [128]
1. Multisensory robot controller
2. Operation (Phase E)
3. Ground demonstration for rendezvous and proximity operations on a non-cooperative spacecraft

> *"Argon was designed to provide sensing capabilities for relative navigation during proximity, rendezvous, and docking operations between spacecraft."* [128]

   - a) Rendezvous
   - b) Proximity operations: inspection/
4. 2012

MDA SIS – McDonald Dettwiler Associates's Space Infrastructure Servicing [126]
1. Servicing spacecraft
2. Concept (Phase 0)
3. General servicing
   a) Rendezvous
   b) Proximity operations: inspection/grappling/docking
   c) Servicing: repair/ORU/fluid transfer/manoeuvring/de-orbit
4. 2011

ATK MEV – Vivisat/ATK Mission Extension Vehicle [126]
1. Servicing spacecraft
2. Concept (Phase 0/A*/B*)
3. Lifetime extension / Recover
   a) Rendezvous
   b) Proximity operations: grappling/docking
   c) Servicing: manoeuvring/re-orbit
4. 2012

RRM – Robotic Refueling Mission (Phase 1) [16] [12]
1. Multisensory/multitask robot
2. Operation (Phase E)
3. Robotic manipulation and fluid transfer
   a) *"Launch Lock Removal and Vision - The Dextre robot releases the "launch locks" on the four RRM servicing tools. These locks kept the tools secure within the RRM module during the shuttle Atlantis' flight to the International Space Station. Then Dextre's cameras image the hardware in both sunlight and darkness, providing data to develop machine vision algorithms that work against harsh on-orbit lighting."*
   b) *"Gas Fittings Removal - Marking the first use of RRM tools on orbit, Dextre uses the tools to remove the fittings that many spacecraft have for the filling of special coolant gases."* [12]
   c) *"Refueling - After snipping lock wires and removing caps, Dextre is able to access a fuel valve similar to those commonly used on satellites today and transfer liquid ethanol through a sophisticated robotic fueling hose, completing a first-of-its-kind robotic refueling event."* [12]
   d) *"SMA (Sub-miniature A) Cap Removal - Dextre removes the coaxial radio frequency (RF) connector caps that terminate and protect the RF connector while the satellite is in orbit. These are known as "SMA (Sub-miniature A) caps." Access to these connectors would allow a robotic servicer to plug into the data systems of a satellite and better diagnose an internal issue."* [12]
   e) *"Screw Removal - Dextre will robotically unscrew satellite bolts (fasteners). RRM draws from its experience with the Hubble Space Telescope servicing mission in its use of a small cage to guide the tool tip and ensure that no fasteners float away."* [12]
   f) *"Thermal Blanket Manipulation - Dextre slices off thermal blanket tape and folds back a thermal blanket to access the contents underneath."* [12]
4. 2015 (ongoing)

VIPIR – Visual Inspection Poseable Invertebrate Robot [16] [129]
1. Robotic system
2. Operation (Phase E)
3. Inspection/telepresence
4. 2015

Raven [127] [130]
1. Multisensory robot platform/controller* (* ARGON continuation)
2. Development/operation (Phase D/E**)
3. Real-time and relative navigation for rendezvous and proximity operations on a non-cooperative spacecraft
4. 2016 (*to be launched)

CleanSpace One [126] [131]
1. Servicing spacecraft
2. Concept (Phase 0/A*)

> *"The development of the approach and capture systems has passed the prototype stage, which involved making critical choices for the project. The next stage will combine putting together the first version of*

the engineering models – which will be more accurate than the prototypes – and more extensive tests."

3. Active debris removal of a specific target (cubesat)

   a) Rendezvous
   b) Proximity operations: acquisition/grappling/docking

4. 2018

TRUSSELATOR [132] [33]

1. Structural elements fabrication device
2. Concept (Phase 0) (TRL-4 ground prototype developed)
3. Truss fabrication
4. 2016

SpiderFab (Bot) [33]

1. Servicing spacecraft (robotic assembly in orbit)
2. Concept (Phase 0)
3.
4. 2020

Phoenix [46]

1. Servicing spacecraft
2. Concept/development (Phase 0/A)
   (*Considering the individual developments from other related DARPA projects such as OE, TRUSSELATOR, SpiderFab)
3. GEO robotics servicing, life extension:
   a) Rendezvous
   b) Proximity operation: acquisition/grappling/docking
   c) Servicing: exchange, repair, harvest, assemble
4. 2020

e.Deorbit [134]

1. Servicing spacecraft
2. Concept (Phase A)
3. Active debris removal of a specific target (Envisat)
   a) Rendezvous
   b) Proximity operations: acquisition/grappling/docking
   c) Servicing: de-orbit
4. 2021

CESSORS – Chinese Experimental Space System for On-orbit Robotistic Services [115]

1. Servicing spacecraft
2. Concept (Phase 0)
3. General servicing, rescue and recover
   "The aim of this project is to develop a small space robotic system, which is capable of orbit maneuvering and implementing unmanned robotic servicing, such as repairing or retrieving malfunction satellites. CESSORS consists of robotic manipulator system, target detecting system, free-flying platform, micro-target system and ground teleoperation system." [115]
   a) Rendezvous
   b) Proximity operations: acquisition/grappling
   c)
4. 2006

Appendix D – Orbital Manoeuvres

The equations for Circular Coplanar Phasing are used as presented by Vallado [156]:

$$\omega_{client} = \sqrt{\frac{\mu}{{a_{client}}^3}} \tag{D-1}$$

$$T_{phase} = \frac{k_{client}\,(2\pi) + \theta_{phase}}{\omega_{client}} \tag{D-2}$$

$$a_{phase} = \left[\mu\left(\frac{T_{phase}}{k_{servicer}\,(2\pi)}\right)^2\right]^{1/3} \tag{D-3}$$

$$\Delta V_{phase} = 2\left|\sqrt{\frac{2\mu}{a_{client}} - \frac{\mu}{a_{phase}}} - \sqrt{\frac{\mu}{a_{client}}}\right| \tag{D-4}$$

ω_{client} = Client angular velocity;
T_{phase} = Time for phasing manoeuvre;
a_{phase} = Semi-major axis for phasing manoeuvre;
ΔV_{phase} = ΔV for phasing manoeuvre;
$k_{servicer}$ = Number of Servicer revolutions before rendezvous;
k_{client} = Number of Client revolutions before rendezvous;
θ_{phase} = Phase angle (Servicer and Client angular separation);

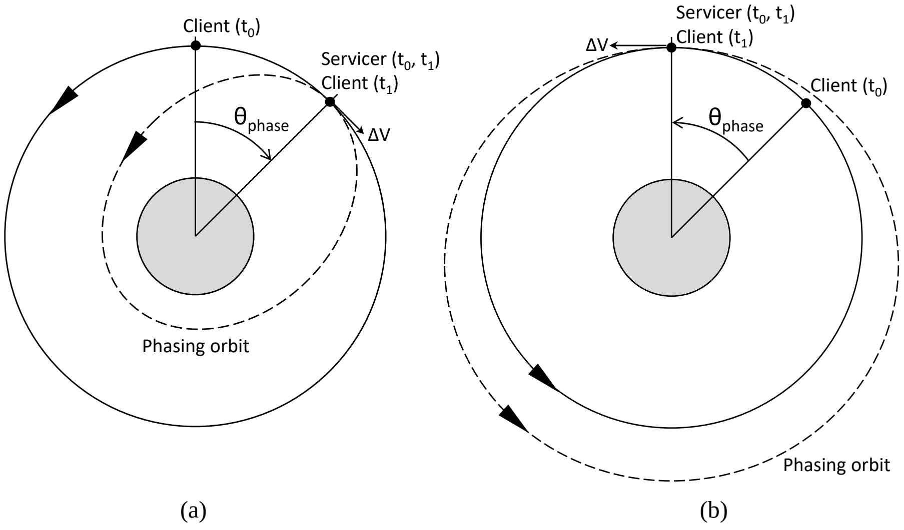


Figure D-1 – Phasing Manoeuvres (adapted from [156]**) – (a) Client leading Servicer, (b) Servicer leading Client**

Appendix E – *Utility* function and obsolescence time

In a real use case, the definition of the expected Obsolescence Time (T_{obs}) is particular to each user, operator or area. Herein the assumption used for T_{obs} aims to replicate what is observed for satellites' designed life and their effective operational life using resources publicly available such as Seradata (2018). Figure E-1 presents the normal distribution of the ratio between the age of the satellite at the moment of retirement (End-of-Life – EOL) and the initial Design Life. This gives an estimate of how much the systems outlive their initial design life.

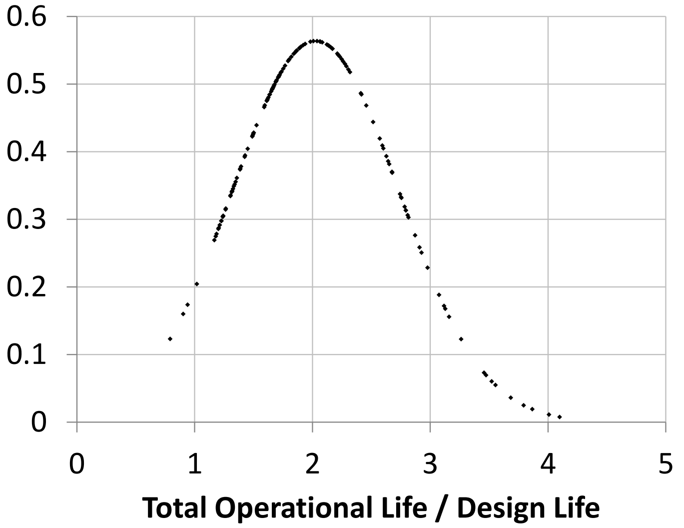


Figure E-1 – Overlife estimation for Commercial Geostationary satellites launched between 01/01/1990 and 09/09/2018 (normal retirement) - Sample = 144 satellites

As suggested by the Figure E-1, operators might still find use or *Utility* out of their systems beyond the initial design life, suggesting a longer obsolescence time for the Payload. In this way, an over-life of 50% is assumed for the Payload, therefore:

$$T_{obsPayload} = 1.5t_{life} \quad \textbf{(E-5)}$$

Such value is considered as a conservative estimate based on the most common values and the threshold presented in Figure E-1. For a satellite designed for 15 years (t_{life} = 15) and overlife of 50%, the correction for the Bus can be estimated. Using the *Utility* function with $T_{obs} = t_{life}$ and $t = t_{overlife}$, the *Utility* at the end of the operational life is calculated. This value is assumed to be the residual *Utility* that led the satellite operator to not want to use the satellite anymore *U(EOL)*.

$$\mathrm{U(EOL)} = 1\mathrm{e}^{\left[-\left(\frac{22.5}{15}\right)^2\right]} \quad \textbf{(E-6)}$$

$$\mathrm{U(EOL)} = 0.105 \quad \textbf{(E-7)}$$

Using the *Utility* function with $U(t) = U(EOL)$ and $t = t_{life}$, the obsolescence time to be corrected is calculated.

$$0.105 = 1\mathrm{e}^{\left[-\left(\frac{15}{\mathrm{T_{obs}}}\right)^2\right]} \quad \textbf{(E-8)}$$

$$\mathrm{T_{obscorrect}} = 10\mathrm{years} \quad \textbf{(E-9)}$$

As the *Utility* function can have a slower decay, in order to enable the Bus *Utility* to reach the minimum residual *Utility* calculated ($U(t) = U(EOL)$), the calculation of the factor is presented:

$$\mathrm{T_{obsPayload}} = 0.67\mathrm{t_{life}} \quad \textbf{(E-10)}$$

It is important to note that this estimate can vary depending on the user preferences and could even make use of more sophisticated methods based on proprietary information and heritage.

Appendix F – *Reliability*: Weibull Function Parameters

- Sample start date: 01/01/2000
- Sample censor date: 31/12/2017
- Number of satellites: 535
- β: 0.3607
- θ: 69112.52 years

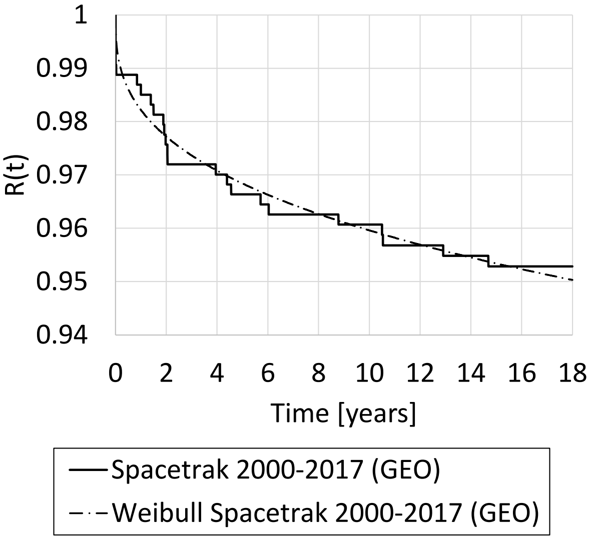


Figure F-1 – Weibull distribution and fit

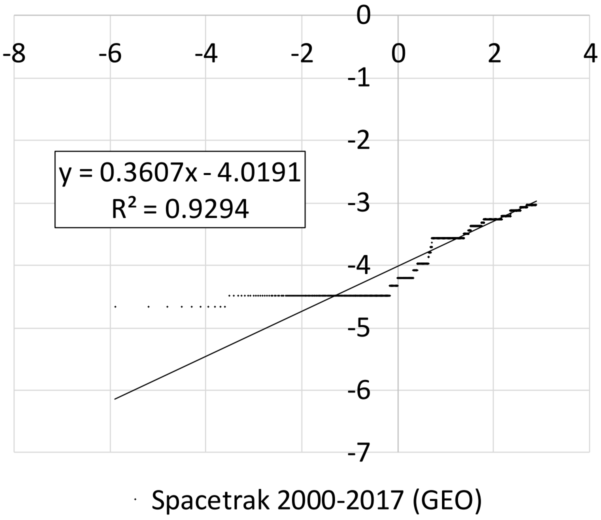
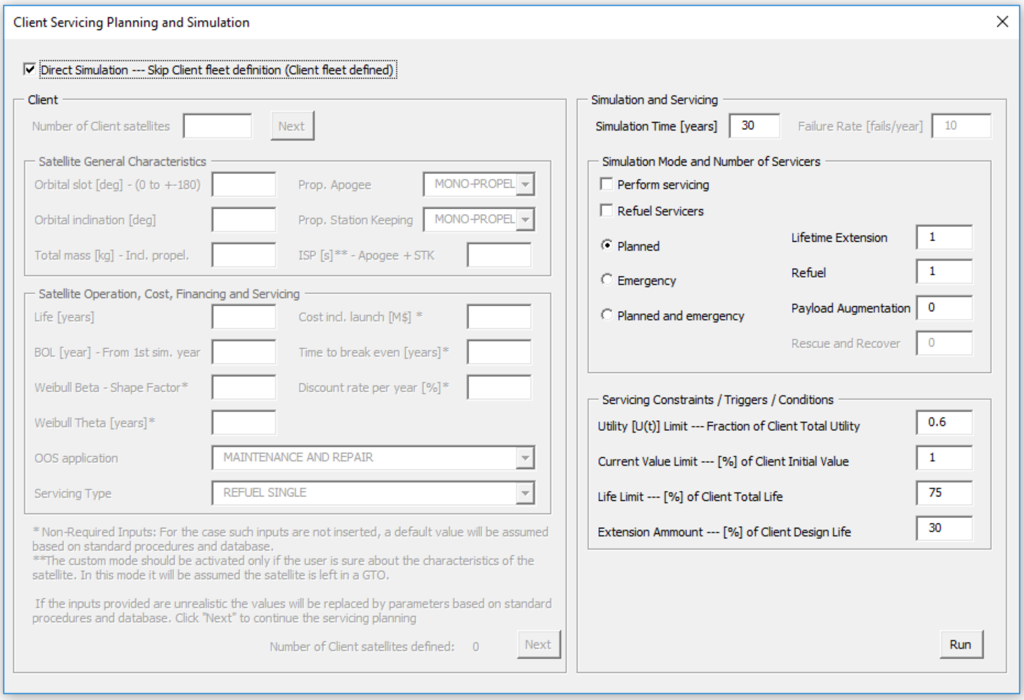


Figure F-2 – Weibull distribution and fit

Appendix G – Framework Summary

- **Lines of code:** Over 5900 including comments, headings and interfaces
- **Number of primary modules:** 17
- **Number of auxiliary modules:** 35 (including input and output handling modules)
- **Main interfaces and VBA Environment**



☑ Direct Simulation --- Skip Client fleet definition (Client fleet defined)

Prop. Apogee: MONO-PROPEL

Prop. Station Keeping: MONO-PROPEL

OOS application: MAINTENANCE AND REPAIR

Servicing Type: REFUEL SINGLE

* Non-Required Inputs: For the case such inputs are not inserted, a default value will be assumed based on standard procedures and database.
**The custom mode should be activated only if the user is sure about the characteristics of the satellite. In this mode it will be assumed the satellite is left in a GTO.

If the inputs provided are unrealistic the values will be replaced by parameters based on standard procedures and database. Click "Next" to continue the servicing planning

Number of Client satellites defined: 0

Simulation Time [years]: 30

Failure Rate [fails/year]: 10

☐ Perform servicing

☐ Refuel Servicers

● Planned

○ Emergency

○ Planned and emergency

Lifetime Extension: 1

Refuel: 1

Payload Augmentation: 0

Rescue and Recover: 0

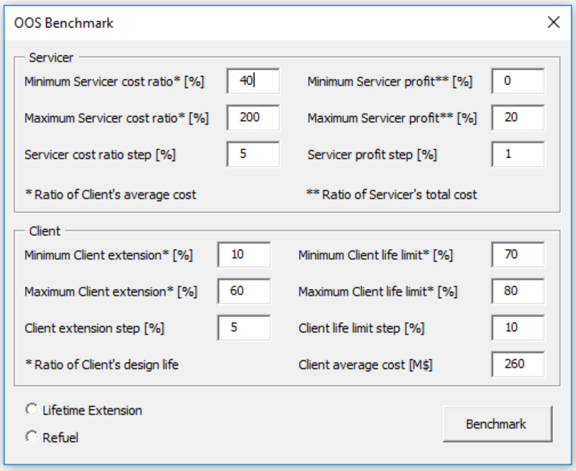
Utility [U(t)] Limit --- Fraction of Client Total Utility: 0.6

Current Value Limit --- [%] of Client Initial Value: 1

Life Limit --- [%] of Client Total Life: 75

Extension Ammount --- [%] of Client Design Life: 30

Figure G-1 – Main input interface



Minimum Servicer cost ratio* [%]: 40

Maximum Servicer cost ratio* [%]: 200

Servicer cost ratio step [%]: 5

Minimum Servicer profit** [%]: 0

Maximum Servicer profit** [%]: 20

Servicer profit step [%]: 1

* Ratio of Client's average cost

** Ratio of Servicer's total cost

Minimum Client extension* [%]: 10

Maximum Client extension* [%]: 60

Client extension step [%]: 5

Minimum Client life limit* [%]: 70

Maximum Client life limit* [%]: 80

Client life limit step [%]: 10

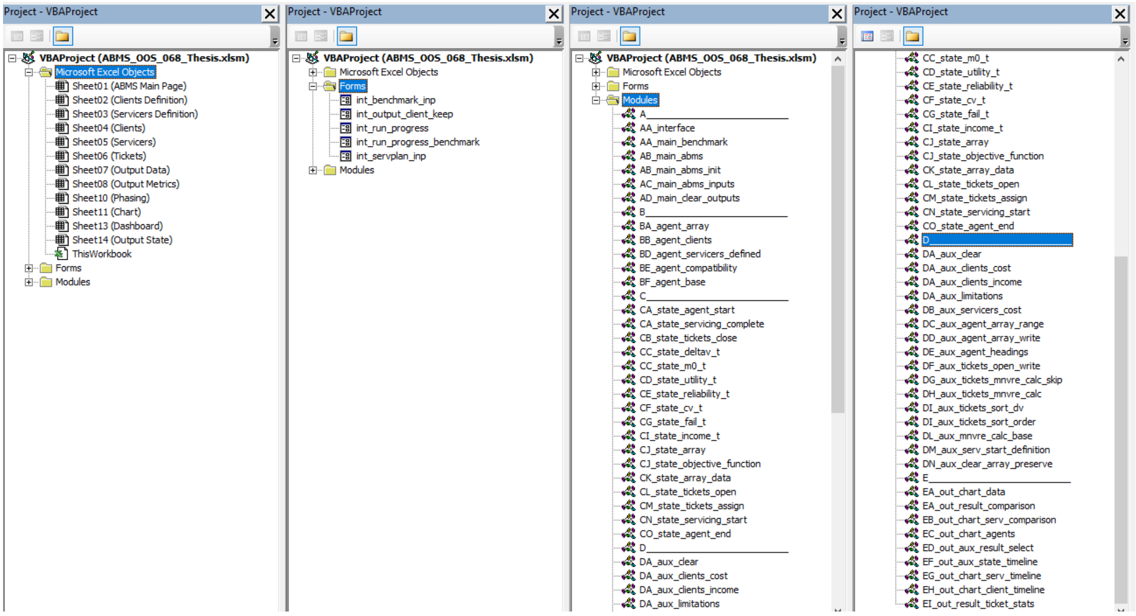
* Ratio of Client's design life

Client average cost [M$]: 260

○ Lifetime Extension

○ Refuel

Figure G-2 – Solution Exploration input interface



- VBAProject (ABMS_OOS_068_Thesis.xlsm)
  - Microsoft Excel Objects
    - Sheet01 (ABMS Main Page)
    - Sheet02 (Clients Definition)
    - Sheet03 (Servicers Definition)
    - Sheet04 (Clients)
    - Sheet05 (Servicers)
    - Sheet06 (Tickets)
    - Sheet07 (Output Data)
    - Sheet08 (Output Metrics)
    - Sheet10 (Phasing)
    - Sheet11 (Chart)
    - Sheet13 (Dashboard)
    - Sheet14 (Output State)
    - ThisWorkbook
  - Forms
  - Modules

- VBAProject (ABMS_OOS_068_Thesis.xlsm)
  - Microsoft Excel Objects
  - Forms
    - int_benchmark_inp
    - int_output_client_keep
    - int_run_progress
    - int_run_progress_benchmark
    - int_servplan_inp
  - Modules

- VBAProject (ABMS_OOS_068_Thesis.xlsm)
  - Microsoft Excel Objects
  - Forms
  - Modules
    - A____________________
    - AA_interface
    - AA_main_benchmark
    - AB_main_abms
    - AB_main_abms_init
    - AC_main_abms_inputs
    - AD_main_clear_outputs
    - B____________________
    - BA_agent_array
    - BB_agent_clients
    - BD_agent_servicers_defined
    - BE_agent_compatibility
    - BF_agent_base
    - C____________________
    - CA_state_agent_start
    - CA_state_servicing_complete
    - CB_state_tickets_close
    - CC_state_deltav_t
    - CC_state_m0_t
    - CD_state_utility_t
    - CE_state_reliability_t
    - CF_state_cv_t
    - CG_state_fail_t
    - CI_state_income_t
    - CJ_state_array
    - CJ_state_objective_function
    - CK_state_array_data
    - CL_state_tickets_open
    - CM_state_tickets_assign
    - CN_state_servicing_start
    - CO_state_agent_end
    - D____________________
    - DA_aux_clear
    - DA_aux_clients_cost
    - DA_aux_clients_income
    - DA_aux_limitations

- CC_state_m0_t
- CD_state_utility_t
- CE_state_reliability_t
- CF_state_cv_t
- CG_state_fail_t
- CI_state_income_t
- CJ_state_array
- CJ_state_objective_function
- CK_state_array_data
- CL_state_tickets_open
- CM_state_tickets_assign
- CN_state_servicing_start
- CO_state_agent_end
- D____________________
- DA_aux_clear
- DA_aux_clients_cost
- DA_aux_clients_income
- DA_aux_limitations
- DB_aux_servicers_cost
- DC_aux_agent_array_range
- DD_aux_agent_array_write
- DE_aux_agent_headings
- DF_aux_tickets_open_write
- DG_aux_tickets_mnvre_calc_skip
- DH_aux_tickets_mnvre_calc
- DI_aux_tickets_sort_dv
- DI_aux_tickets_sort_order
- DL_aux_mnvre_calc_base
- DM_aux_serv_start_definition
- DN_aux_clear_array_preserve
- E____________________
- EA_out_chart_data
- EA_out_result_comparison
- EB_out_chart_serv_comparison
- EC_out_chart_agents
- ED_out_aux_result_select
- EF_out_aux_state_timeline
- EG_out_chart_serv_timeline
- EH_out_chart_client_timeline
- EI_out_result_ticket_stats

Figure G-3 – VBA Environment – Objects, Forms and Modules

- **Total running time**
  - Case 1: 103 seconds (Population 1), 103 seconds (Population 2), 100 seconds (Population 3)
  - Case 2: 10 seconds
  - Case 3: 12 seconds
  - Case 4: 10 seconds
  - Solution Exploration (Case 2): 736 seconds (MR), 440 seconds (LE)

The main module of the framework (*main_abms*) is presented as follows. From this module, all the primary and auxiliary modules are called as described in Chapter 5 and illustrated in Figure 5-2 and from Figure 5-3 to Figure 5-6.

```
'=================================================================================================================
' AGENT BASED MODEL FOR ON-ORBIT SERVICING MISSIONS (ABMS_OOS_068.XLSM ABMS_OOS_068.XLSM)
'-----------------------------------------------------------------------------------------------------------------
' Tiago Matos - t.h.matosdecarvalho@cranfield.ac.uk - 14/12/2018
'-----------------------------------------------------------------------------------------------------------------
' Modules are identified according to the order of call and the functions: [XX_FUNCTION_name_description]
' [AX] MAIN - Modules with main routines
' [BX] AGENT - Modules with agent definition
' [CX] STATE - Modules with state definition and transition
' [DX] AUX - Modules with auxiliary calculations and processes for the other modules
' [EX] OUT - Modules with output calculations and handling
'-----------------------------------------------------------------------------------------------------------------
' Variables, parameters, methods or assumptions are all summarized in an auxiliary spreadsheet. Once one of such
' items is used, a comment will indicate its source in the auxiliary spreadsheet.
'-----------------------------------------------------------------------------------------------------------------

'=================================================================================================================

Sub main_abms()

'-----------------------------------------------------------------------------------------------------------------
' BASIC VARIABLES AND INITIAL SETUP
'-----------------------------------------------------------------------------------------------------------------
sim_set_start_filter:                                          'Return point for NPV filtering
If benchmark_mode = 0 Then
    Application.ScreenUpdating = False                         'Disable Screen Updating
    Application.DisplayAlerts = False                          'Disable Excel alerts
    i_run = 0                                                  'Simulation initial run identifier
End If
sim_set_start:                                                 'Return point for multiple simulation runs
Call main_abms_inputs                                          'Main inputs definition
'-----------------------------------------------------------------------------------------------------------------
'-----------------------------------------------------------------------------------------------------------------
' AGENTS SETUP
'-----------------------------------------------------------------------------------------------------------------
Call aux_limitations                                           'Check Excel limitations for the simulation
Call aux_clear                                                 'Clear all the worksheets and data outputs
Call agent_array                                               'Variable arrays redimensioning
Call agent_clients                                             'Agents definition - Clients
Call agent_servicers_defined                                   'Agents definition - Servicer
Call agent_compatibility                                       'Clients/Servicers compatibility
Call agent_base                                                'Refuelling/Resupplying Base parameters
Call aux_agent_headings                                        'Heading of the spreadsheet
Call aux_agent_array_range                                     'Variable ranges definition
Call aux_agent_array_write                                     'Writing on the spreadsheet
'-----------------------------------------------------------------------------------------------------------------
'-----------------------------------------------------------------------------------------------------------------
' SIMULATION START
'-----------------------------------------------------------------------------------------------------------------
For t = 0 To n_steps_time                                      'Loop the t from 0 to the end of the simulation
    curr_time = t * step_time / year_day                       'Current time of the simulation in [years]
    Call state_agent_start                                     'Check if Client starts operation at timestep t
    Call state_servicing_complete                              'Check if for Tickets completed at timestep t
    Call state_tickets_close                                   'Check for open Tickets to be closed at timestep t
    If i_run > 0 Then Call aux_mnvre_calc_base                 'Check Servicer limits to return for refuelling
    If (sim_mode = 2 Or sim_mode = 3) Then Call state_fail_t   'Check for Client failure for timestep t
    Call state_deltav_t                                        'Clients/Servicers DeltaV Prop. Mass for timestep t
    Call state_utility_t                                       'Clients Utility for timestep t
    Call state_reliability_t                                   'Clients Reliability for timestep t
    Call state_cv_t                                            'Clients CV for timestep t
    Call state_income_t                                        'Clients Income for timestep t
    Call state_objective_function                              'Clients Objective Function for timestep t
    Call state_array                                           'Update States
    Call state_array_data                                      'Write data for all metrics for the step t
    Call state_tickets_open                                    'Open tickets
    If (sim_mode = 1 And i_run > 0) Or _
       (sim_mode = 2 And i_run > 0) Or _
       (sim_mode = 3 And i_run > 0) Then                       'Conditions to call Tickets opening
        Call aux_tickets_mnvre_calc_skip                       'Check the option to skip the manoeuvre calc.
        If (i_tickets > 0) And (skip_manoeuvre = 0) Then       'Check the option to skip the manoeuvre calc.
            Call aux_tickets_mnvre_calc                        'Calculate the manoeuvre to reach the Client
            Call aux_tickets_sort_order                        'Sort the Tickets based on the order
            Call aux_tickets_assign                            'Assign the Tickets to the available Servicers
        End If
    End If
    Call state_servicing_start                                 'Calculate the service beginning time
    If (sim_mode = 1 And i_run > 0) Or _
       (sim_mode = 2 And i_run > 0) Or _
       (sim_mode = 3 And i_run > 0) Then _
        Call out_aux_state_timeline                            'Operation timeline for each agent
    pctCompl = (t / n_steps_time) * 100                        'Graphic interface status bar
    progress pctCompl                                          'Graphic interface status bar
Next t                                                         'Next timestep
If i_run = 0 Then Call aux_serv_start_definition               'Define the Servicer initial conditions
Call state_agent_end                                           'Check if Client ends operation at timestep t
Call clear_array_preserve                                      'Clear Ticket dynamic arrays before the next run
If benchmark_mode = 0 Then i_run = i_run + 1                   'Simulation run counter
If benchmark_mode = 0 And _
   serv_plan_start = 1 And _
   i_run <= 1 Then GoTo sim_set_start                          'Check if Servicer adjustment for BOL
'-----------------------------------------------------------------------------------------------------------------
```

```
'-----------------------------------------------------------------------------------------------------------------
' OUTPUT HANDLING
'-----------------------------------------------------------------------------------------------------------------
Call out_result_comparison                                    'Client comparison with and without servicing

filter_client = False                                         'Manual NPV Filter (as applied to Use Cases)
npv_filter = 5                                                'Minimum NPV to filter
If filter_client = True Then                                  'Routine to loop main_abms
    Call out_filter
    If loop_stop = 0 Then GoTo sim_set_start_filter
End If

If benchmark_mode = 0 Then                                    'Create/process charts if not a benchmark run
    Call out_chart_data                                       'Charts for each of the agents' metrics
    Call out_chart_agents                                     'Chart with the agents' orbital location
    Call out_chart_serv_comparison                            'Chart with Clients' metric comparison
    Call out_chart_serv_timeline                              'Chart with Servicers' timelines
    Call out_chart_client_timeline                            'Chart with Clients' timelines
    Call out_result_ticket_stats                              'Info about Tickets for each application
    Unload int_run_progress                                   'Unload interface
    Application.ScreenUpdating = True                         'Restore conditions
    Application.DisplayAlerts = True                          'Restore conditions
    Sheet13.Activate                                          'Result worksheet
    End                                                       'End all variables
End If
'-----------------------------------------------------------------------------------------------------------------
End Sub
```

Appendix H – Client Samples, SpaceTrak Filters and Servicing Tickets

H.1 Client Sample and SpaceTrak Filters

The samples of Clients are presented with the input information to be used in the framework. Apart from servicing and financial aspects, the information comes directly from SpaceTrak using the filters presented in Figure H-1.

Table H-1 – Sample 1 – Population 1 (part 1)

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
JCSAT-2	154	0.3	2280	BP	BP	GTO	10	1.000	156.87	4.0	6	NONE	NONE	-	-
LEASAT 5 (Integral)	72	3	6895	BP	BP	GTO	7	1.023	390.94	2.8	6	LE	FULL SK	-	-
INSAT 1D	68	0.2	1190	BP	BP	GTO	7	1.444	111.24	2.8	6	MR	REFUEL SINGLE	-	-
DFS 2 KOPERNIKUS	38	0.1	1415	BP	BP	GTO	10	1.561	120.37	4.0	6	MR	REFUEL SINGLE	-	-
TDF-2	36	1.4	1318	BP	BP	GTO	9	1.561	116.42	3.6	6	NONE	NONE	-	-
BS-3A	110	0.2	1100	MP	MP	GTO	7	1.656	104.70	2.8	6	MR	REFUEL SINGLE	-	-
EUTELSAT II-F1	76	1.3	1878	BP	BP	GTO	9	1.663	139.98	3.6	6	NONE	NONE	-	-
SBS 6	279	0.1	2478	BP	BP	GTO	10	1.781	165.37	4.0	6	MR	REFUEL SINGLE	-	-
INMARSAT 2-F1	109	2.6	1385	BP	BP	GTO	10	1.830	119.11	4.0	6	NONE	NONE	-	-
GSTAR 4	255	0	1300	MP	MP	GTO	10	1.888	112.22	4.0	6	MR	REFUEL SINGLE	-	-
SATCOM C-1	322	0.1	1170	MP	MP	GTO	12	1.888	106.84	4.8	6	MR	REFUEL SINGLE	-	-
EUTELSAT II-F2	48	0.1	1878	BP	BP	GTO	9	2.041	139.98	3.6	6	MR	REFUEL SINGLE	-	-
ITALSAT 1	13.2	0.1	1867	BP	BP	GTO	5	2.041	140.26	2.0	6	MR	REFUEL SINGLE	-	-
ASTRA 1B	19.2	0.2	2495	MP	MP	GTO	10	2.164	160.00	4.0	6	NONE	NONE	-	-
METEOSAT 5	62	1	681	MP	MP	GTO	5	2.164	87.98	2.0	6	MR	REFUEL SINGLE	-	-
INMARSAT 2-F2	218	2.7	824	BP	BP	GTO	10	2.183	95.58	4.0	6	NONE	NONE	-	-
TELESAT ANIK E-2	279	0	2950	MP	MP	GTO	12	2.257	178.08	4.8	6	NONE	NONE	-	-
SPACENET 4	172	0	1271	MP	MP	GTO	10	2.277	111.08	4.0	6	MR	REFUEL SINGLE	-	-
AURORA II (SATCOM C-5)	221	0.1	1338	MP	MP	GTO	12	2.408	113.43	4.8	6	NONE	NONE	-	-
TDRS 5 (IUS)	192	0.1	2120	MP	MP	GTO	10	2.585	144.81	4.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 605	174	0	4296	BP	BP	GTO	13	2.619	246.63	5.2	6	NONE	NONE	-	-
BS-3B	110	0.2	1100	MP	MP	GTO	7	2.648	104.70	2.8	6	MR	REFUEL SINGLE	-	-
TELESAT ANIK E-1	250	0	2950	MP	MP	GTO	12	2.737	178.08	4.8	6	NONE	NONE	-	-
INTELSAT 601	312.5	0	4330	BP	BP	GTO	13	2.827	248.26	5.2	6	NONE	NONE	-	-
EUTELSAT II-F3	21.5	0.1	1878	BP	BP	GTO	10	2.934	139.81	4.0	6	MR	REFUEL SINGLE	-	-
INMARSAT 2-F3	202	2.7	1385	BP	BP	GTO	10	2.959	119.11	4.0	6	NONE	NONE	-	-
TELECOM 2A	3	0	2275	BP	BP	GTO	10	2.959	156.66	4.0	6	MR	REFUEL SINGLE	-	-
INSAT 2DT	82	0.1	1310	BP	BP	GTO	7	3.156	116.31	2.8	6	MR	REFUEL SINGLE	-	-
SUPERBIRD B1	162	0.1	2500	BP	BP	GTO	7	3.156	167.08	2.8	6	MR	REFUEL SINGLE	-	-
INMARSAT 2-F4	107	2.1	1385	BP	BP	GTO	10	3.290	119.11	4.0	6	NONE	NONE	-	-
TELECOM 2B	47	0	2275	BP	BP	GTO	10	3.290	156.66	4.0	6	MR	REFUEL SINGLE	-	-
NSS-K	338.5	0.1	2836	MP	BP	GTO	10	3.441	175.73	4.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT II-F4	347	0.1	1878	BP	BP	GTO	9	3.523	139.98	3.6	6	MR	REFUEL SINGLE	-	-
INSAT 2A	47	0.2	1900	BP	BP	GTO	7	3.523	141.27	2.8	6	MR	REFUEL SINGLE	-	-
OPTUS B1	164	0.3	2800	BP	BP	GTO	14	3.619	178.34	5.6	6	NONE	NONE	-	-
SATCOM C-4	225	0.1	791	MP	MP	GTO	12	3.667	91.90	4.8	6	MR	REFUEL SINGLE	-	-
HISPASAT 1A	352	0	2194	BP	BP	GTO	10	3.696	153.20	4.0	6	MR	REFUEL SINGLE	-	-
SATCOM C-3	281	0.1	784	MP	MP	GTO	12	3.696	91.62	4.8	6	MR	REFUEL SINGLE	-	-
HELLAS-SAT 1	39	0.1	1428	BP	BP	GTO	10	3.782	120.91	4.0	6	MR	REFUEL SINGLE	-	-
GALAXY 7	235	0.2	2968	BP	BP	GTO	12	3.825	186.18	4.8	6	NONE	NONE	-	-
SUPERBIRD A1	158	0.1	2780	BP	BP	GTO	7	3.918	179.35	2.8	6	MR	REFUEL SINGLE	-	-
TDRS 6 (IUS)	314	0.1	2180	MP	MP	GTO	10	4.037	147.22	4.0	6	MR	REFUEL SINGLE	-	-
ASTRA 1C	2	0	2790	BP	BP	GTO	15	4.362	177.68	6.0	6	MR	REFUEL SINGLE	-	-
HGS-4 (GALAXY 4)	261	0.3	2980	BP	BP	GTO	14	4.482	186.18	5.6	6	NONE	NONE	-	-
HISPASAT 1B	330	0	2208	BP	BP	GTO	10	4.559	153.80	4.0	6	MR	REFUEL SINGLE	-	-
INSAT 2B	93.5	0.2	1900	BP	BP	GTO	7	4.559	141.27	2.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 701 (IS-701)	330.5	0	3650	BP	BP	GTO	15	4.809	215.77	6.0	6	MR	REFUEL SINGLE	-	-
METEOSAT 6	67	1.2	704	MP	MP	GTO	5	4.888	88.93	2.0	6	MR	REFUEL SINGLE	-	-
SOLIDARIDAD 1	250.8	0	2776	BP	BP	GTO	14	4.888	177.30	5.6	6	MR	REFUEL SINGLE	-	-
TELSTAR 401	263	0.1	3375	MP	MP	GTO	12	4.959	195.97	4.8	6	LE	FULL SK	-	-
DIRECTV 1	269	0	2860	BP	BP	GTO	12	4.965	181.45	4.8	6	NONE	NONE	-	-
GALS 01	42	0.2	2500	E	E	GTO	7	5.056	180.01	2.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 702	32.9	1	3695	BP	BP	GTO	18	5.461	216.92	7.2	6	MR	REFUEL SINGLE	-	-
BS-3N	110	0.2	1210	MP	MP	GTO	7	5.520	109.09	2.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 2 (PAS 2)	174	0.1	2920	BP	BP	GTO	15	5.520	183.32	6.0	6	MR	REFUEL SINGLE	-	-
TELESAT NIMIQ 4i (DIRECTV 2)	259.2	0	2860	BP	BP	GTO	12	5.592	181.45	4.8	6	NONE	NONE	-	-
BRASILSAT B1	291	0.4	1765	BP	BP	GTO	12	5.611	134.75	4.8	6	NONE	NONE	-	-
TURKSAT 1B	31	0.1	1779	BP	BP	GTO	10	5.611	135.64	4.0	6	MR	REFUEL SINGLE	-	-
OPTUS B3	164	0.8	2800	BP	BP	GTO	14	5.657	178.34	5.6	6	MR	REFUEL SINGLE	-	-
NSS-703	313	0.2	3720	BP	BP	GTO	14	5.765	219.29	5.6	6	MR	REFUEL SINGLE	-	-
SOLIDARIDAD 2	247	0.2	2776	BP	BP	GTO	14	5.770	177.30	5.6	6	MR	REFUEL SINGLE	-	-

Table H-2 – Sample 1 – Population 1 (part 2)

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
EXPRESS 2 (1R)	346	0.2	2500	E	E	GTO	5	5.785	179.99	2.0	6	MR	REFUEL SINGLE	-	-
ASTRA 1D	287	0.1	2920	BP	BP	GTO	15	5.836	183.32	6.0	6	MR	REFUEL SINGLE	-	-
TELSTAR 11 (ORION 1)	322.5	0.1	2361	BP	BP	GTO	12	5.913	159.91	4.8	6	NONE	NONE	-	-
LUCH 1 (LOUCH 1)	344	2.6	2200	E	E	GTO	5	5.960	165.52	2.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 704	66	0	3661	BP	BP	GTO	14	6.027	216.60	5.6	6	MR	REFUEL SINGLE	-	-
INTELSAT 705	330.5	0	3650	BP	BP	GTO	14	6.223	216.09	5.6	6	MR	REFUEL SINGLE	-	-
BRASILSAT B2	292	0.1	1780	BP	BP	GTO	12	6.241	135.38	4.8	6	MR	REFUEL SINGLE	-	-
HOT BIRD 1	15	0	1870	BP	BP	GTO	11	6.241	139.31	4.4	6	MR	REFUEL SINGLE	-	-
MSAT 2 (AMSC 1)	257	0	2855	BP	BP	GTO	12	6.268	181.23	4.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 706	157	0	4180	BP	BP	GTO	14	6.376	240.71	5.6	6	MR	REFUEL SINGLE	-	-
GOES 09	160	0.2	2105	BP	BP	GTO	5	6.392	150.48	2.0	6	MR	REFUEL SINGLE	-	-
TELESAT NIMIQ 3	269	0	2934	BP	BP	GTO	12	6.441	184.69	4.8	6	MR	REFUEL SINGLE	-	-
TDRS 7 (IUS)	84.5	0.3	2225	MP	MP	GTO	10	6.533	149.04	4.0	6	LE	FULL SK	-	-
INTELSAT 4 (PAS 4)	72	0.1	3043	BP	BP	GTO	15	6.592	190.40	6.0	6	MR	REFUEL SINGLE	-	-
JCSAT-3	128	0.1	1820	BP	BP	GTO	12	6.660	137.05	4.8	6	MR	REFUEL SINGLE	-	-
NSTAR A	132	0	3410	BP	BP	GTO	10	6.661	206.53	4.0	6	MR	REFUEL SINGLE	-	-
TELSTAR 402R	271	0.2	3410	MP	MP	GTO	13	6.732	197.06	5.2	6	MR	REFUEL SINGLE	-	-
LUCH 2 (LUCH 2-1)	77	3.1	2400	E	E	GTO	5	6.780	175.15	2.0	6	MR	REFUEL SINGLE	-	-
ASTRA 1E	23.7	0.1	3010	BP	BP	GTO	14	6.800	187.49	5.6	6	MR	REFUEL SINGLE	-	-
GALS 02	42	0.2	2500	E	E	GTO	7	6.881	180.01	2.8	6	MR	REFUEL SINGLE	-	-
INSAT 2C	47	0.2	2106	BP	BP	GTO	7	6.934	150.07	2.8	6	MR	REFUEL SINGLE	-	-
TELECOM 2C	3	0.1	2283	BP	BP	GTO	10.255	6.934	156.95	4.1	6	MR	REFUEL SINGLE	-	-
GALAXY 3R	286	0.1	2980	BP	BP	GTO	13.51	6.956	186.31	5.4	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 1	283	0.1	3287	MP	MP	GTO	12	6.993	192.23	4.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 3R (PAS 3R)	279	0.1	2918	BP	BP	GTO	14	7.036	183.47	5.6	6	MR	REFUEL SINGLE	-	-
ABS-1A (KOREASAT 2)	67	0	1464	MP	MP	GTO	12	7.040	118.38	4.8	6	MR	REFUEL SINGLE	-	-
PAKSAT 1 (PALAPA C1)	38	0.1	2989	BP	BP	GTO	14	7.088	186.57	5.6	6	MR	REFUEL SINGLE	-	-
NSTAR B	136	0	3420	BP	BP	GTO	10	7.099	206.99	4.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 707	307	0.4	4175	BP	BP	GTO	15	7.204	240.10	6.0	6	MR	REFUEL SINGLE	-	-
ASTRA 1F	44.5	0.1	3010	BP	BP	GTO	15	7.274	187.24	6.0	6	MR	REFUEL SINGLE	-	-
MSAT 1	252.5	0	2855	BP	BP	GTO	12	7.307	181.23	4.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 24 (AMOS 1)	31	0.1	996	BP	BP	GTO	12	7.375	102.70	4.8	6	MR	REFUEL SINGLE	-	-
PALAPA C2	146	0	2989	BP	BP	GTO	15	7.375	186.32	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 709	47.5	0	3420	BP	BP	GTO	14	7.458	205.68	5.6	6	MR	REFUEL SINGLE	-	-
ARABSAT 2A	19	0.1	2617	BP	BP	GTO	12	7.526	170.90	4.8	6	MR	REFUEL SINGLE	-	-
TURKSAT 1C	31	0	1757	BP	BP	GTO	10	7.526	134.71	4.0	6	MR	REFUEL SINGLE	-	-
ITALSAT 2	16	0.1	1983	BP	BP	GTO	7	7.607	144.81	2.8	6	LE	FULL SK	-	-
TELECOM 2D	352	0	2260	BP	BP	GTO	10	7.607	156.02	4.0	6	MR	REFUEL SINGLE	-	-
EXPRESS 1-2	102	0	2500	E	E	GTO	5	7.742	179.99	2.0	6	MR	REFUEL SINGLE	-	-
ARABSAT 2B	34.5	0.1	2661	BP	BP	GTO	12	7.874	172.80	4.8	6	MR	REFUEL SINGLE	-	-
AMC-2	275.5	0.1	2649	MP	BP	GTO	15	8.086	178.50	6.0	6	MR	REFUEL SINGLE	-	-
NAHUEL 1A	288	0.1	1790	BP	BP	GTO	12	8.086	135.80	4.8	6	LE	FULL SK	-	-
INTELSAT 26 (JCSAT 4)	65.9	0.1	3105	BP	BP	GTO	12	8.134	192.23	4.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 801	330.5	0.1	3420	MP	BP	GTO	10	8.167	200.75	4.0	6	LE	FULL SK	-	-
DIRECTV 6 (TEMPO 2)	250	0.6	3400	BP	BP	GTO	12	8.187	205.41	4.8	6	MR	REFUEL SINGLE	-	-
THAICOM 3	78.5	0.1	2652	BP	BP	GTO	14	8.296	171.95	5.6	6	MR	REFUEL SINGLE	-	-
GOES 10	300	0.5	2105	BP	BP	GTO	5	8.318	300.00	2.0	6	LE	FULL SK	-	-
GALAXY 25 (TELSTAR 5)	267	0	3650	BP	BP	GTO	15	8.399	215.77	6.0	6	MR	REFUEL SINGLE	-	-
INSAT 2D	74	0.2	2079	BP	BP	GTO	10	8.427	148.31	4.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 802	32.9	0	3435	MP	BP	GTO	10	8.488	201.41	4.0	6	MR	REFUEL SINGLE	-	-
SUPERBIRD 3 (SUPERBIRD C)	158	0	3130	BP	BP	GTO	13	8.575	193.05	5.2	6	MR	REFUEL SINGLE	-	-
PANAMSAT 6	317	0.1	3420	BP	BP	GTO	15	8.606	205.39	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 5 (PAS 5)	223	0.1	3720	E	BP	GTO	15	8.660	232.08	6.0	6	MR	REFUEL SINGLE	-	-
METEOSAT 7	57	1.8	703	MP	MP	GTO	5	8.677	88.89	2.0	6	MR	REFUEL SINGLE	-	-
W75/ABS-1B (HOT BIRD 3)	74	0.4	2915	BP	BP	GTO	14.51	8.677	183.22	5.8	6	MR	REFUEL SINGLE	-	-
EAGLE 1 (AMC-3)	288	0.1	2845	MP	BP	GTO	15	8.681	175.12	6.0	6	MR	REFUEL SINGLE	-	-
NSS-5	50.5	0.1	3455	MP	BP	GTO	14	8.734	201.26	5.6	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 3	272.8	0	3674	MP	MP	GTO	13	8.767	208.42	5.2	6	MR	REFUEL SINGLE	-	-
TELSTAR 10/APSTAR IIR	76.5	0.1	3747	BP	BP	GTO	15	8.797	220.20	6.0	6	MR	REFUEL SINGLE	-	-
KUPON 1	55	0	2600	E	E	GTO	6	8.870	184.86	2.4	6	MR	REFUEL SINGLE	-	-
ASTRA 5A (SIRIUS 2)	31	0.1	2937	BP	BP	GTO	12	8.871	184.82	4.8	6	MR	REFUEL SINGLE	-	-

Table H-3 – Sample 1 – Population 1 (part 3)

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
JCSAT-1B (JCSAT-5)	150	0.2	2982	BP	BP	GTO	12	8.926	186.80	4.8	6	MR	REFUEL SINGLE	-	-
ASTRA 1G	56.8	0	3388	BP	BP	GTO	15	8.926	203.96	6.0	6	MR	REFUEL SINGLE	-	-
GALAXY 8I	265	0	3548	E	BP	GTO	15	8.942	223.68	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 804	175	0.1	3455	MP	BP	GTO	10	8.978	202.28	4.0	6	MR	REFUEL SINGLE	-	-
BRASILSAT B3	296.8	0	1780	BP	BP	GTO	12	9.101	150.00	4.8	6	MR	REFUEL SINGLE	-	-
EUTELSAT 16B (HOT BIRD 4)	16	0.1	2885	BP	BP	GTO	12	9.164	182.54	4.8	6	MR	REFUEL SINGLE	-	-
NSS-806	312.5	0.1	3500	MP	BP	GTO	12	9.164	203.71	4.8	6	MR	REFUEL SINGLE	-	-
NILESAT 101	353	0	1840	BP	BP	GTO	15	9.329	137.48	6.0	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 4	283	0	3478	MP	MP	GTO	12	9.353	200.38	4.8	6	MR	REFUEL SINGLE	-	-
CHINASAT 5A/APSTAR 9A (CHINASTAR-1)	125.5	0.1	2984	MP	BP	GTO	15	9.415	180.94	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 805	169	0.1	3525	MP	BP	GTO	10	9.468	205.35	4.0	6	MR	REFUEL SINGLE	-	-
PSN V (SINOSAT 1)	142	0.1	2830	BP	BP	GTO	15	9.549	179.41	6.0	6	MR	REFUEL SINGLE	-	-
ST-1	142	0	3255	BP	BP	GTO	12	9.655	198.90	4.8	6	MR	REFUEL SINGLE	-	-
ASTRA 2A	100	0.2	3635	E	BP	GTO	15	9.666	227.92	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 7 (PAS 7)	342	0	3838	BP	BP	GTO	15	9.713	224.38	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT W2	16	0.1	2950	BP	BP	GTO	12	9.767	185.39	4.8	6	MR	REFUEL SINGLE	-	-
EUTELSAT 4B (HOT BIRD 5)	4	0	2994	BP	BP	GTO	14	9.778	226.00	5.6	6	MR	REFUEL SINGLE	-	-
AFRISTAR 1	21	0	2739	BP	BP	GTO	15	9.830	175.48	6.0	6	MR	REFUEL SINGLE	-	-
AMC-5	279.1	0	1720	BP	BP	GTO	12	9.830	132.87	4.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 8 (PAS 8)	168.9	0	3800	BP	BP	GTO	15	9.847	222.63	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 115 WEST A (SATMEX 5)	268	60.1	4144	BP	BP	GTO	15	9.934	238.64	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 6B (PAS 6B)	317	0.1	3594	E	BP	GTO	15	9.978	225.92	6.0	6	MR	REFUEL SINGLE	-	-
GALAXY 26 (INTELSAT 3006)	50	0.1	3763	BP	BP	GTO	15	10.129	220.93	6.0	6	MR	REFUEL SINGLE	-	-
JCSAT-6	150	0.1	2900	BP	BP	GTO	12	10.132	183.20	4.8	6	MR	REFUEL SINGLE	-	-
ARABSAT 3A (BADR 3)	29	0	2708	BP	BP	GTO	15	10.161	174.14	6.0	6	MR	REFUEL SINGLE	-	-
ASIASAT 3S	146	0.1	3480	E	BP	GTO	15	10.222	220.39	6.0	6	MR	REFUEL SINGLE	-	-
INSAT 2E	83	0.1	2550	BP	BP	GTO	12	10.255	168.01	4.8	6	MR	REFUEL SINGLE	-	-
EUTELSAT 48C (W3)	48	0	3183	BP	BP	GTO	14	10.285	195.12	5.6	6	MR	REFUEL SINGLE	-	-
TELESAT NIMIQ 1	273.5	0.1	3600	MP	BP	GTO	12	10.389	208.10	4.8	6	MR	REFUEL SINGLE	-	-
ASTRA 1H	292.8	0.5	3690	E	BP	GTO	15	10.466	230.61	6.0	6	MR	REFUEL SINGLE	-	-
TELKOM 1	108	0.1	2763	MP	BP	GTO	15	10.619	171.71	6.0	6	MR	REFUEL SINGLE	-	-
ABS-7 (KOREASAT 3)	116.1	0	2790	MP	BP	GTO	15	10.682	172.83	6.0	6	MR	REFUEL SINGLE	-	-
YAMAL 101	49	0.1	1360	E	E	GTO	10	10.687	125.84	4.0	6	MR	REFUEL SINGLE	-	-
YAMAL 102	89	0.1	1360	E	E	GTO	10	10.687	125.84	4.0	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 5	211	0.2	3500	BP	BP	GTO	12	10.732	209.93	4.8	6	MR	REFUEL SINGLE	-	-
GALAXY 27 (INTELSAT 3007)	66	0.1	3792	BP	BP	GTO	15	10.738	222.27	6.0	6	MR	REFUEL SINGLE	-	-
ABS-6 (ABS-1)	159	0	3740	MP	BP	GTO	15	10.742	213.49	6.0	6	MR	REFUEL SINGLE	-	-
DIRECTV 1R	304.2	0.1	3446	E	BP	GTO	15	10.778	218.74	6.0	6	MR	REFUEL SINGLE	-	-
TELSTAR 12 (ORION 2)	251	0.1	3814	BP	BP	GTO	13	10.803	223.96	5.2	6	MR	REFUEL SINGLE	-	-
AMC-4	225	0.3	3903	MP	BP	GTO	15	10.874	220.73	6.0	6	MR	REFUEL SINGLE	-	-
GALAXY 11	45	0	4484	BP	BP	GTO	15	10.978	254.87	6.0	6	MR	REFUEL SINGLE	-	-
GALAXY 10R	237	0.1	3651	E	BP	GTO	15	11.071	228.70	6.0	6	MR	REFUEL SINGLE	-	-
HISPASAT 84W-1 (HISPASAT 1C)	276.3	0.1	3112	BP	BP	GTO	15	11.099	191.71	6.0	6	MR	REFUEL SINGLE	-	-
ACES GARUDA 1	123	3	4300	MP	BP	GTO	15	11.122	441.20	6.0	6	MR	REFUEL SINGLE	-	-
SUPERBIRD B2 (SUPERBIRD 4)	162	0.1	4057	BP	BP	GTO	13	11.137	235.29	5.2	6	MR	REFUEL SINGLE	-	-
EXPRESS A2 (EXPRESS 6A)	145	0.2	2600	E	E	GTO	10	11.200	184.93	4.0	6	MR	REFUEL SINGLE	-	-
ASIASTAR 1	105	0.1	2777	BP	BP	GTO	12	11.227	177.83	4.8	6	MR	REFUEL SINGLE	-	-
INSAT 3B	83	0	2114	BP	BP	GTO	10	11.227	149.80	4.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 16C (SESAT 1)	14.5	0	2500	E	BP	GTO	10	11.301	175.87	4.0	6	MR	REFUEL SINGLE	-	-
GALAXY 4R	283	0.1	3716	E	BP	GTO	15	11.304	231.88	6.0	6	MR	REFUEL SINGLE	-	-
GOES 11	225	0.3	2117	BP	BP	GTO	5	11.343	250.00	2.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 36A (W4)	347.2	0.1	3190	BP	BP	GTO	14	11.403	195.43	5.6	6	MR	REFUEL SINGLE	-	-
EXPRESS A3	38	0.1	2600	E	E	GTO	10	11.485	184.93	4.0	6	MR	REFUEL SINGLE	-	-
TDRS 8	89	7.1	3180	BP	BP	GTO	11	11.503	195.86	4.4	6	MR	REFUEL SINGLE	-	-
BERMUDASAT 1 (ECHOSTAR 6)	263.8	0.2	3600	BP	BP	GTO	12	11.540	214.48	4.8	6	MR	REFUEL SINGLE	-	-
INTELSAT 9 (PAS 9)	330.5	0	3659	BP	BP	GTO	15	11.581	216.18	6.0	6	MR	REFUEL SINGLE	-	-
BRASILSAT B4	268	0.1	1750	BP	BP	GTO	12	11.636	134.12	4.8	6	MR	REFUEL SINGLE	-	-
NILESAT 102	353	0.01	1827	BP	BP	GTO	15	11.636	136.94	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 4A (EUTELSAT W1)	4	0.1	3250	BP	BP	GTO	12	11.690	198.68	4.8	6	MR	REFUEL SINGLE	-	-
AMC-7	225	0.1	1983	MP	BP	GTO	15	11.712	139.91	6.0	6	MR	REFUEL SINGLE	-	-
ASTRA 2B	19.4	0.2	3315	BP	BP	GTO	15	11.712	200.70	6.0	6	MR	REFUEL SINGLE	-	-

Table H-4 – Sample 1 – Population 2 (part 1)

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
NSS-11	176	10	3552	MP	BP	GTO	15	1	205.24	6.0	6	NONE	NONE	-	-
NSAT-110 (JCSAT 110)	110	0.1	3520	MP	BP	GTO	15	1.014	203.85	6.0	6	NONE	NONE	-	-
THURAYA 1A/GEM 1	52.7	6.4	5108	BP	BP	GTO	12	1.053	287.30	4.8	6	NONE	NONE	-	-
AMC-6	277	0	3901	MP	BP	GTO	15	1.055	220.64	6.0	6	NONE	NONE	-	-
INTELSAT 12 (PAS 12) (EUROPE*STAR 1)	45	0	4150	BP	BP	GTO	15	1.075	238.92	6.0	6	NONE	NONE	-	-
INTELSAT 1R (PAS 1R)	157.1	0.1	4793	E	BP	GTO	15	1.124	286.74	6.0	6	NONE	NONE	-	-
TELESAT ANIK F-1	252.7	0.1	4852	E	BP	GTO	16	1.14	289.24	6.4	6	NONE	NONE	-	-
AMC-8	221	0	2015	MP	BP	GTO	15	1.217	141.20	6.0	6	NONE	NONE	-	-
TURKSAT 2A (EURASIASAT 1)	41.9	0.1	3535	BP	BP	GTO	15	1.277	210.56	6.0	6	NONE	NONE	-	-
EUTELSAT 33C (EUROBIRD 1)	33	0.1	2950	BP	BP	GTO	12	1.433	185.39	4.8	6	MR	REFUEL SINGLE	-	-
XM-2 (XM-ROCK)	333	0.1	4682	E	BP	GTO	15	1.46	280.89	6.0	6	NONE	NONE	-	-
XM-1 (XM-ROLL)	291.4	0.1	4682	E	BP	GTO	6.7507	1.6	286.73	2.7	6	LE	FULL SK	-	-
INTELSAT 10 (PAS 10)	47.5	0.7	3739	BP	BP	GTO	15	1.617	219.83	6.0	6	NONE	NONE	-	-
INTELSAT 901	330.5	7.1	4723	BP	BP	GTO	13	1.686	267.42	5.2	6	NONE	NONE	-	-
ASTRA 2C	23.7	0.1	3643	E	BP	GTO	15	1.705	228.31	6.0	6	NONE	NONE	-	-
GOES 12	300	0.3	2279	BP	BP	GTO	5	1.807	380.00	2.0	6	LE	FULL SK	-	-
INTELSAT 902	62	0.1	4723	BP	BP	GTO	13	1.911	267.42	5.2	6	NONE	NONE	-	-
EUTELSAT 12 WEST B (ATLANTIC BIRD 2)	347.5	0	3150	BP	BP	GTO	12	1.984	194.22	4.8	6	MR	REFUEL SINGLE	-	-
DIRECTV 4S	259	0.1	4260	E	BP	GTO	15	2.154	259.07	6.0	6	NONE	NONE	-	-
INSAT 3C	93.5	0.2	2650	BP	BP	GTO	7	2.313	173.63	2.8	6	LE	FULL SK	-	-
ECHOSTAR 7	241	0.1	4026	MP	MP	GTO	15	2.391	222.98	6.0	6	NONE	NONE	-	-
INTELSAT 904	45	0.1	4723	BP	BP	GTO	13	2.396	267.42	5.2	6	NONE	NONE	-	-
JCSAT-2A (JCSAT-8)	93	0	2600	BP	BP	GTO	11	2.488	170.40	4.4	6	MR	REFUEL SINGLE	-	-
INTELSAT 903	328.5	0.1	4726	BP	BP	GTO	13	2.493	267.57	5.2	6	NONE	NONE	-	-
NSS-7	340	0	4708	MP	BP	GTO	15	2.54	257.83	6.0	6	NONE	NONE	-	-
DIRECTV 5	250	0.1	3640	BP	BP	GTO	15	2.597	215.32	6.0	6	NONE	NONE	-	-
INTELSAT 905	335.5	0.1	4723	BP	BP	GTO	13	2.675	267.42	5.2	6	NONE	NONE	-	-
EXPRESS A-1R (A4)	145	0.2	2600	E	E	GTO	10	2.688	184.93	4.0	6	MR	REFUEL SINGLE	-	-
GALAXY 3C	264.9	0.1	4850	E	BP	GTO	15	2.704	289.77	6.0	6	NONE	NONE	-	-
EUTELSAT 5 WEST A (STELLAT 5)	355	0.1	4050	BP	BP	GTO	15	2.759	250.00	6.0	6	NONE	NONE	-	-
NSTAR C	136	0.1	1645	MP	BP	GTO	10	2.759	126.87	4.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 70D (HOT BIRD 6)	70.3	0.1	3900	BP	BP	GTO	12	2.888	228.32	4.8	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 8	283	0.1	4660	BP	BP	GTO	15	2.888	263.44	6.0	6	NONE	NONE	-	-
EUTELSAT 59A (ATLANTIC BIRD 1)	59.3	0	2700	BP	BP	GTO	15	2.907	173.80	6.0	6	NONE	NONE	-	-
METEOSAT 8 (MSG 1)	41.5	2	2100	BP	BP	GTO	7	2.907	149.81	2.8	6	LE	FULL SK	-	-
INTELSAT 906	64.1	0.1	4723	BP	BP	GTO	13	2.93	267.42	5.2	6	NONE	NONE	-	-
METSAT-1 (KALPANA 1)	73	0.48	1055	BP	BP	GTO	7	2.947	105.54	2.8	6	MR	REFUEL SINGLE	-	-
HISPASAT 30W-4 (HISPASAT 1D)	330	0.1	3272	BP	BP	GTO	15	2.964	198.79	6.0	6	NONE	NONE	-	-
EUTELSAT 33B (W5)	33	0.1	3170	BP	BP	GTO	12	3.137	195.11	4.8	6	MR	REFUEL SINGLE	-	-
TDRS 10	186	7	3190	BP	BP	GTO	11	3.176	196.31	4.4	6	NONE	NONE	-	-
NSS-6	95	6	4750	MP	BP	GTO	14	3.211	250.00	5.6	6	NONE	NONE	-	-
TELESAT NIMIQ 2	332	0.1	3600	MP	BP	GTO	13	3.244	207.83	5.2	6	MR	REFUEL SINGLE	-	-
INTELSAT 907	332.5	0.1	4685	BP	BP	GTO	13	3.374	265.54	5.2	6	NONE	NONE	-	-
GALAXY 12 (PANAMSAT LIGHT 1)	231	0	1760	MP	BP	GTO	15	3.521	130.99	6.0	6	NONE	NONE	-	-
INSAT 3A	93.5	0.1	2958	BP	BP	GTO	12	3.521	185.74	4.8	6	MR	REFUEL SINGLE	-	-
PAKSAT-MULTI MISSION INTERIM	38.2	0.1	4042	BP	BP	GTO	15	3.526	233.85	6.0	6	NONE	NONE	-	-
GSAT-2	48	0.05	1823	BP	BP	GTO	7	3.597	138.00	2.8	6	MR	REFUEL SINGLE	-	-
HELLAS-SAT 2 (APR-3)	39	0.1	3440	BP	BP	GTO	15	3.614	180.20	6.0	6	NONE	NONE	-	-
AMC-9	277	0.1	4100	BP	BP	GTO	15	3.679	236.57	6.0	6	NONE	NONE	-	-
THURAYA 2	44	6.3	5177	BP	BP	GTO	12	3.689	290.85	4.8	6	NONE	NONE	-	-
OPTUS AND DEFENCE C1	156	0.1	4725	BP	BP	GTO	15	3.693	266.64	6.0	6	NONE	NONE	-	-
ECHOSTAR 12 (RAINBOW 1)	273.6	0.1	4328	MP	BP	GTO	18	3.792	239.18	7.2	6	NONE	NONE	-	-
ECHOSTAR 9/GALAXY 23	239	0	4737	BP	BP	GTO	15	3.85	267.23	6.0	6	NONE	NONE	-	-
INSAT 3E	55	0.11	2778	BP	BP	GTO	12	3.989	177.88	4.8	6	NONE	NONE	-	-
GALAXY 13/HORIZONS 1	233	0.1	4060	E	BP	GTO	15	3.998	248.96	6.0	6	NONE	NONE	-	-
YAMAL 201	90	0.1	1330	E	E	GTO	12	4.146	70.00	4.8	6	MR	REFUEL SINGLE	-	-
YAMAL 202	49	0.2	1330	E	E	GTO	12	4.146	70.00	4.8	6	MR	REFUEL SINGLE	-	-
AMOS-2	356	0.1	1370	BP	BP	GTO	12	4.238	118.28	4.8	6	MR	REFUEL SINGLE	-	-
EXPRESS AM-22	80.1	0	2600	E	BP	GTO	12	4.241	179.83	4.8	6	NONE	NONE	-	-
AMC-10	225	0.1	2340	MP	MP	GTO	15	4.348	152.37	6.0	6	NONE	NONE	-	-
ABS-4/MOBISAT 1	61	0.1	4143	E	BP	GTO	12	4.447	254.85	4.8	6	NONE	NONE	-	-

Table H-5 – Sample 1 – Population 2 (part 2)

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
EUTELSAT 7A (W3A)	7	0	4240	BP	BP	GTO	12	4.455	244.37	4.8	6	NONE	NONE	-	-
EXPRESS AM-11	96.5	0	2542	E	E	GTO	12	4.57	182.19	4.8	6	MR	REFUEL SINGLE	-	-
DIRECTV 7S	241	0.1	5483	BP	BP	GTO	15	4.591	305.27	6.0	6	NONE	NONE	-	-
AMC-11	229	0	2316	MP	MP	GTO	15	4.633	151.41	6.0	6	NONE	NONE	-	-
INTELSAT 10-02	359	0.2	5576	BP	BP	GTO	13	4.71	311.25	5.2	6	NONE	NONE	-	-
TELESAT ANIK F-2 (WILDBLUE 2)	249	0.2	5950	E	BP	GTO	15	4.795	351.09	6.0	6	NONE	NONE	-	-
AMAZONAS 1/HISPASAT 55W-1	324	0.1	4545	BP	BP	GTO	15	4.844	237.00	6.0	6	NONE	NONE	-	-
GSAT-3 (EDUSAT)	74	0	1950	BP	BP	GTO	7	4.971	143.40	2.8	6	MR	REFUEL SINGLE	-	-
AMC-15	255	0.1	4021	MP	BP	GTO	15	5.038	226.02	6.0	6	NONE	NONE	-	-
EXPRESS AM-1	40	0.1	2542	E	E	GTO	12	5.079	182.19	4.8	6	MR	REFUEL SINGLE	-	-
AMC-16	275	0	4200	MP	MP	GTO	15	5.213	110.00	6.0	6	NONE	NONE	-	-
NSS-10	322.5	0	4974	BP	BP	GTO	16	5.343	278.61	6.4	6	NONE	NONE	-	-
XTAR-EUR	29	0.06	3631	BP	BP	GTO	15	5.37	214.91	6.0	6	NONE	NONE	-	-
HIMAWARI 06 (GMS 06/MTSAT 1R)	140	0.1	2900	BP	BP	GTO	15	5.407	182.45	6.0	6	NONE	NONE	-	-
XM-3 (XM-RHYTHM)	275	0.1	4703	E	BP	GTO	15	5.414	281.99	6.0	6	NONE	NONE	-	-
INMARSAT 4-F1	143.5	3	5950	BP	BP	GTO	13	5.444	331.56	5.2	6	NONE	NONE	-	-
EXPRESS AM-2	80	0.1	2598	E	BP	GTO	12	5.493	179.74	4.8	6	NONE	NONE	-	-
APSTAR 6	134	0.1	4680	BP	BP	GTO	14	5.53	264.85	5.6	6	NONE	NONE	-	-
SPACEWAY 1	257.1	0.3	6080	BP	BP	GTO	12.6	5.568	339.04	5.0	6	NONE	NONE	-	-
DIRECTV 8	259	0.1	3750	BP	BP	GTO	15	5.641	220.34	6.0	6	NONE	NONE	-	-
GALAXY 28	271	0	5493	E	BP	GTO	15	5.728	324.91	6.0	6	NONE	NONE	-	-
EXPRESS AM-3	103	0.1	2600	E	BP	GTO	12	5.731	179.83	4.8	6	NONE	NONE	-	-
THAICOM 4/MEASAT 5 (IPSTAR-1)	119.5	0.04	6505	E	BP	GTO	15	5.861	440.00	6.0	6	NONE	NONE	-	-
GALAXY 14 (PANAMSAT LIGHT 2)	235	0	2087	MP	BP	GTO	15	5.869	144.09	6.0	6	NONE	NONE	-	-
TELESAT ANIK F-1R	252.7	0.1	4500	BP	BP	GTO	15	5.94	255.64	6.0	6	NONE	NONE	-	-
GALAXY 15 (PANAMSAT LIGHT 3)	226.9	0.1	2033	MP	BP	GTO	15	6.036	227.50	6.0	6	MR	REFUEL SINGLE	-	-
INMARSAT 4-F2	64	3	5950	BP	BP	GTO	13	6.106	331.56	5.2	6	NONE	NONE	-	-
SPACEWAY 2	260.8	0.3	6116	BP	BP	GTO	12.6	6.129	341.06	5.0	6	NONE	NONE	-	-
TELKOM 2	157	0	1975	MP	BP	GTO	15	6.129	195.00	6.0	6	MR	REFUEL SINGLE	-	-
INSAT 4A	83	0.1	3081	BP	BP	GTO	12	6.225	191.17	4.8	6	MR	REFUEL SINGLE	-	-
METEOSAT 9 (MSG 2)	3.3	1.8	2036	BP	BP	GTO	7	6.225	147.08	2.8	6	LE	FULL SK	-	-
EUTELSAT 174A (AMC-23)	174	0	5053	BP	BP	GTO	16	6.244	282.59	6.4	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 10	250	0	4333	MP	BP	GTO	15	6.378	240.25	6.0	6	NONE	NONE	-	-
HIMAWARI 07 (GMS 07/MTSAT 2)	145	0.1	4650	BP	BP	GTO	10	6.385	265.23	4.0	6	LE	FULL SK	-	-
EUTELSAT HOT BIRD 13E (HOT BIRD 7A)	13	0.1	4100	BP	BP	GTO	15	6.444	236.57	6.0	6	NONE	NONE	-	-
JCSAT-5A (JCSAT-9)	132	0	4401	MP	BP	GTO	12	6.532	244.36	4.8	6	MR	REFUEL SINGLE	-	-
ASTRA 1KR	19.2	0.2	4332	MP	BP	GTO	15	6.553	240.20	6.0	6	NONE	NONE	-	-
GOES 13	300	0.5	3209	BP	BP	GTO	10	6.647	331.50	4.0	6	LE	FULL SK	-	-
EUTELSAT 113 WEST A (SATMEX 6)	247	0	5456	BP	BP	GTO	15	6.655	303.85	6.0	6	NONE	NONE	-	-
THAICOM 5	78.5	0	2776	BP	BP	GTO	14	6.655	177.30	5.6	6	NONE	NONE	-	-
KAZSAT 1	103	0	1380	E	E	GTO	12	6.712	126.90	4.8	6	MR	REFUEL SINGLE	-	-
GALAXY 16	261	0.1	4640	BP	BP	GTO	15	6.713	262.46	6.0	6	NONE	NONE	-	-
EUTELSAT HOT BIRD 13B (HOT BIRD 8)	13	0.1	4875	BP	BP	GTO	15	6.844	274.08	6.0	6	NONE	NONE	-	-
JCSAT-3A (JCSAT-10)	128	0	4048	MP	BP	GTO	15	6.863	227.24	6.0	6	NONE	NONE	-	-
KOREASAT 5	113	0	4465	BP	BP	GTO	15	6.891	253.95	6.0	6	NONE	NONE	-	-
DIRECTV 9S	259	0	5535	BP	BP	GTO	15	7.035	308.01	6.0	6	MR	REFUEL SINGLE	-	-
OPTUS D1	160	0.1	2380	MP	BP	GTO	15	7.035	155.96	6.0	6	MR	REFUEL SINGLE	-	-
XM-4 (XM-BLUES)	244.7	0.1	4672	E	BP	GTO	15	7.082	280.36	6.0	6	MR	REFUEL SINGLE	-	-
BADR 4 (ARABSAT 4B)	26	0.1	3280	BP	BP	GTO	15	7.107	199.14	6.0	6	MR	REFUEL SINGLE	-	-
AMC-18	221	0	2081	MP	MP	GTO	15	7.189	142.09	6.0	6	MR	REFUEL SINGLE	-	-
WILDBLUE 1 (ISKY 1)	248.9	0.1	4735	BP	BP	GTO	12	7.189	268.48	4.8	6	MR	REFUEL SINGLE	-	-
MEASAT 3 (A-M SAT)	91.5	0.07	4765	BP	BP	GTO	15	7.197	263.00	6.0	6	MR	REFUEL SINGLE	-	-
ETS 08	147	0.1	6000	BP	BP	GTO	10	7.215	336.21	4.0	6	LE	FULL SK	-	-
INSAT 4B	111.2	0.1	3025	BP	BP	GTO	12	7.444	188.69	4.8	6	MR	REFUEL SINGLE	-	-
TELESAT ANIK F-3	241.3	0.1	4639	BP	BP	GTO	15	7.523	262.41	6.0	6	MR	REFUEL SINGLE	-	-
ASTRA 1L	19.2	0.1	4498	MP	MP	GTO	15	7.592	244.29	6.0	6	MR	REFUEL SINGLE	-	-
GALAXY 17	269	0.1	4100	BP	BP	GTO	15	7.592	236.57	6.0	6	MR	REFUEL SINGLE	-	-
CHINASAT 6B	115.5	0.1	4600	BP	BP	GTO	15	7.761	260.51	6.0	6	MR	REFUEL SINGLE	-	-
DIRECTV 10	257	0.2	5900	E	BP	GTO	15	7.765	348.17	6.0	6	MR	REFUEL SINGLE	-	-
BSAT 3A	110	0.1	1980	MP	BP	GTO	13	7.871	140.01	5.2	6	MR	REFUEL SINGLE	-	-
SPACEWAY 3	265	0.3	6075	BP	BP	GTO	12.6	7.871	338.76	5.0	6	NONE	NONE	-	-

Table H-6 – Sample 1 – Population 2 (part 3)

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
INTELSAT 11 (IS-11)	317	0	2450	BP	BP	GTO	15	8.014	163.11	6.0	6	MR	REFUEL SINGLE	-	-
OPTUS D2	152	0	2350	MP	BP	GTO	15	8.014	154.74	6.0	6	MR	REFUEL SINGLE	-	-
STAR ONE C1	295	0.1	4100	BP	BP	GTO	15	8.123	236.57	6.0	6	MR	REFUEL SINGLE	-	-
ASTRA 4A (SIRIUS 4)	5	0	4385	MP	BP	GTO	15	8.132	242.65	6.0	6	MR	REFUEL SINGLE	-	-
HORIZONS 2	85	0	2350	MP	BP	GTO	15	8.225	154.74	6.0	6	MR	REFUEL SINGLE	-	-
EXPRESS AM-33	96.5	0.1	2600	E	BP	GTO	12	8.326	100.00	4.8	6	NONE	NONE	-	-
THOR 5	359.2	0.1	1960	MP	BP	GTO	15	8.366	138.99	6.0	6	MR	REFUEL SINGLE	-	-
WINDS (KIZUNA)	143	0	4850	MP	MP	GTO	5	8.396	267.20	2.0	6	LE	FULL SK	-	-
DIRECTV 11	260.8	0.1	5923	E	BP	GTO	12	8.469	352.05	4.8	6	NONE	NONE	-	-
D1/ECHOSTAR G1 (ICO-G1)	267	6	6634	BP	BP	GTO	15	8.54	369.44	6.0	6	MR	REFUEL SINGLE	-	-
STAR ONE C2	290	0.1	4100	BP	BP	GTO	15	8.551	236.57	6.0	6	MR	REFUEL SINGLE	-	-
VINASAT 1	132	1.1	2637	MP	BP	GTO	15	8.551	268.00	6.0	6	MR	REFUEL SINGLE	-	-
GALAXY 18	237	0.1	4642	BP	BP	GTO	15	8.64	262.56	6.0	6	MR	REFUEL SINGLE	-	-
CHINASAT 9	92.2	0.1	4500	BP	BP	GTO	15	8.692	255.64	6.0	6	MR	REFUEL SINGLE	-	-
TURKSAT 3A	42	0.1	3110	BP	BP	GTO	15	8.701	191.63	6.0	6	MR	REFUEL SINGLE	-	-
BADR 6 (ARABSAT 4C)	26	0	3346	BP	BP	GTO	15	8.77	202.08	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 25	328.5	0	4191	BP	BP	GTO	15	8.77	240.86	6.0	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 11	250	0	5511	BP	BP	GTO	15	8.793	306.74	6.0	6	MR	REFUEL SINGLE	-	-
AMC-21	235	0	2473	MP	BP	GTO	16	8.874	159.62	6.4	6	MR	REFUEL SINGLE	-	-
SUPERBIRD C2 (SUPERBIRD 7)	144	0	4820	BP	BP	GTO	15	8.874	271.34	6.0	6	MR	REFUEL SINGLE	-	-
INMARSAT 4-F3	262	3	5950	BP	BP	GTO	13	8.885	331.56	5.2	6	MR	REFUEL SINGLE	-	-
TELESAT NIMIQ 4	278	0	4850	BP	BP	GTO	15	8.973	272.84	6.0	6	MR	REFUEL SINGLE	-	-
GALAXY 19	263	0.1	4692	BP	BP	GTO	13	8.985	265.89	5.2	6	MR	REFUEL SINGLE	-	-
ASTRA 1M	19.2	0.2	5320	BP	BP	GTO	15	9.101	296.74	6.0	6	MR	REFUEL SINGLE	-	-
CIEL-2	231	0.1	5561	BP	BP	GTO	15	9.196	309.39	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 48D/AFGHANSAT 1 (W2M)	48	0.1	3463	BP	BP	GTO	15	9.225	207.32	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT HOT BIRD 13C (HOT BIRD 9)	13	0	4880	BP	BP	GTO	15	9.225	274.33	6.0	6	MR	REFUEL SINGLE	-	-
EXPRESS AM-44	349	0.1	2534	E	BP	GTO	12	9.367	100.00	4.8	6	MR	REFUEL SINGLE	-	-
EXPRESS MD-1	80	0	1140	E	E	GTO	10	9.367	115.46	4.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 33E (HOT BIRD 10)	33	0.1	4892	BP	BP	GTO	15	9.373	256.50	6.0	6	MR	REFUEL SINGLE	-	-
NSS-9	183	0.1	2238	MP	BP	GTO	15	9.373	123.50	6.0	6	MR	REFUEL SINGLE	-	-
TELSTAR 11N	322.5	0	4012	E	BP	GTO	15	9.411	170.00	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 10A (W2A)	10	0.1	5922	BP	BP	GTO	15	9.509	264.00	6.0	6	MR	REFUEL SINGLE	-	-
SES-7	108.2	0	3905	E	E	GTO	15	9.625	190.00	6.0	6	MR	REFUEL SINGLE	-	-
MEASAT 3A (1R)	91.5	0.04	2366	MP	BP	GTO	12	9.726	110.15	4.8	6	MR	REFUEL SINGLE	-	-
GOES 14	255	0.4	3211	BP	BP	GTO	10	9.743	351.50	4.0	6	MR	REFUEL SINGLE	-	-
SIRIUS FM-5 (SIRIUS RADIO)	274	0.1	5820	BP	BP	GTO	15	9.75	208.00	6.0	6	MR	REFUEL SINGLE	-	-
T1 (TERRESTAR 1)	248.9	5.9	6910	BP	BP	GTO	15	9.753	450.00	6.0	6	MR	REFUEL SINGLE	-	-
ASIASAT 5	100.5	0	3760	BP	BP	GTO	15	9.866	175.00	6.0	6	MR	REFUEL SINGLE	-	-
JCSAT-RA (JCSAT-12)	128	0.1	4042	MP	MP	GTO	15	9.893	245.00	6.0	6	MR	REFUEL SINGLE	-	-
OPTUS D3	156	0.05	2501	MP	BP	GTO	15	9.893	150.00	6.0	6	MR	REFUEL SINGLE	-	-
TELESAT NIMIQ 5	287.3	0.1	4745	BP	BP	GTO	15	9.967	240.00	6.0	6	MR	REFUEL SINGLE	-	-
AMAZONAS 2	299	0.1	5465	BP	BP	GTO	15	10.01	300.00	6.0	6	MR	REFUEL SINGLE	-	-
NSS-12	57	0	5622	E	BP	GTO	15	10.08	335.00	6.0	6	MR	REFUEL SINGLE	-	-
THOR 6/INTELSAT 1W	359.1	0.04	3049	BP	BP	GTO	15	10.08	190.00	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 14	315	0.1	5614	BP	BP	GTO	15	10.15	290.00	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 36B (W7)	36	0.1	5627	BP	BP	GTO	15	10.15	255.00	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 15 (IS-15)	85.1	0.1	2484	MP	BP	GTO	15	10.17	152.00	6.0	6	MR	REFUEL SINGLE	-	-
DIRECTV 12	257.2	0.1	5900	E	BP	GTO	15	10.25	250.00	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 16 (IS-16)	284	0.1	2450	MP	BP	GTO	15	10.37	149.00	6.0	6	MR	REFUEL SINGLE	-	-
GOES 15	225	0.4	3238	BP	BP	GTO	10	10.43	340.00	4.0	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 14	241	0.1	6379	E	BP	GTO	15	10.47	232.00	6.0	6	MR	REFUEL SINGLE	-	-
ASTRA 3B	23.5	0.1	5470	BP	BP	GTO	15	10.64	343.80	6.0	6	MR	REFUEL SINGLE	-	-
BADR 5 (ARABSAT 5B)	26	0	5420	BP	BP	GTO	15	10.68	230.00	6.0	6	MR	REFUEL SINGLE	-	-
ARABSAT 5A	30.5	0	4839	BP	BP	GTO	15	10.74	270.00	6.0	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 15	298.3	0.1	5521	BP	BP	GTO	15	10.78	275.00	6.0	6	MR	REFUEL SINGLE	-	-
NILESAT 201	353	0	3200	BP	BP	GTO	15	10.85	210.00	6.0	6	MR	REFUEL SINGLE	-	-
RASCOM 1R (RASCOM QAF 1R)	2.9	0	3050	BP	BP	GTO	15	10.85	223.00	6.0	6	MR	REFUEL SINGLE	-	-
CHINASAT 6A (SINOSAT 6)	125	0.4	5100	BP	BP	GTO	15	10.93	170.00	6.0	6	MR	REFUEL SINGLE	-	-
QUASI ZENITH SATELLITE 1 (MICHIBIKI 1)	135	41	4100	BP	BP	GTO	10	10.95	290.00	4.0	6	MR	REFUEL SINGLE	-	-
XM-5	274.8	0	5984	E	BP	GTO	15	11.04	244.00	6.0	6	MR	REFUEL SINGLE	-	-

Table H-7 – Sample 1 – Population 3 (part 1)

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
BSAT 3B	110	0	2060	MP	BP	GTO	15	1	265.00	6.0	6	MR	REFUEL SINGLE	-	-
SKYTERRA 1	258.7	6.1	5360	BP	BP	GTO	15	1.046	306.00	6.0	6	NONE	NONE	-	-
HYLAS 1	326.5	0	2300	BP	BP	GTO	15	1.079	205.00	6.0	6	NONE	NONE	-	-
INTELSAT 17	66	0.1	5540	BP	BP	GTO	15	1.079	273.00	6.0	6	NONE	NONE	-	-
EUTELSAT KA-SAT 9A (KA-SAT)	9	0.1	6150	BP	BP	GTO	15	1.162	445.00	6.0	6	NONE	NONE	-	-
HISPASAT 30W-5 (HISPASAT 1E)	330	0.1	5320	BP	BP	GTO	15	1.17	280.00	6.0	6	NONE	NONE	-	-
KOREASAT 6	116	0	2622	MP	BP	GTO	15	1.17	171.00	6.0	6	NONE	NONE	-	-
ELEKTRO-L N1	345.5	0.4	1797	MP	BP	GTO	10	1.229	150.00	4.0	6	MR	REFUEL SINGLE	-	-
AL YAH 1 (YAHSAT 1A)	52.5	0	5935	BP	BP	GTO	15	1.482	365.00	6.0	6	NONE	NONE	-	-
INTELSAT 28 (NEW DAWN)	33	0.1	3000	MP	BP	GTO	15	1.482	320.00	6.0	6	MR	REFUEL SINGLE	-	-
GSAT-8 (INSAT 4G)	55	0.1	3091	BP	BP	GTO	12	1.559	121.40	4.8	6	NONE	NONE	-	-
ST-2	88	0	5090	BP	BP	GTO	15	1.559	232.00	6.0	6	NONE	NONE	-	-
KAZSAT 2	86.5	0.1	1330	E	BP	GTO	12.255	1.711	121.75	4.9	6	MR	REFUEL SINGLE	-	-
SES-3	257	0.1	3112	MP	BP	GTO	15	1.711	200.00	6.0	6	NONE	NONE	-	-
GSAT-12	83	0.1	1410	BP	BP	GTO	7	1.711	78.00	2.8	6	LE	FULL SK	-	-
ASTRA 1N	19.2	0.1	5330	BP	BP	GTO	15	1.773	378.00	6.0	6	NONE	NONE	-	-
BSAT 3C (JCSAT-110R)	110	0	2910	MP	BP	GTO	16	1.773	135.00	6.4	6	NONE	NONE	-	-
ARABSAT 5C	20	0.1	4630	BP	BP	GTO	15	1.899	315.00	6.0	6	NONE	NONE	-	-
SES-2	273	0	3152	MP	BP	GTO	15	1.899	235.00	6.0	6	NONE	NONE	-	-
EUTELSAT 7 WEST A (ATLANTIC BIRD 7)	353	0	4600	BP	BP	GTO	15	1.907	255.10	6.0	6	NONE	NONE	-	-
QUETZSAT 1	283	0.1	5514	E	BP	GTO	15	1.92	271.50	6.0	6	NONE	NONE	-	-
INTELSAT 18 (IS-18)	180	0	3200	MP	BP	GTO	15	1.937	178.00	6.0	6	NONE	NONE	-	-
EUTELSAT 16A (W3C)	16	0.1	5370	BP	BP	GTO	15	1.941	236.00	6.0	6	NONE	NONE	-	-
VIASAT-1	244.9	0	6740	E	BP	GTO	15	1.975	372.00	6.0	6	NONE	NONE	-	-
ASIASAT 7	105.5	0	3813	BP	BP	GTO	15	2.076	135.00	6.0	6	NONE	NONE	-	-
AMOS-5	17	0.1	1880	E	BP	GTO	15	2.119	197.00	6.0	6	NONE	NONE	-	-
LUCH 5A	167	4.9	1150	E	BP	GTO	10	2.119	113.91	4.0	6	NONE	NONE	-	-
NIGCOMSAT 1R	42.5	0.27	5088	BP	BP	GTO	15	2.142	190.00	6.0	6	NONE	NONE	-	-
SES-4	338	0.1	6180	BP	BP	GTO	15	2.298	320.00	6.0	6	NONE	NONE	-	-
INTELSAT 22	72.1	0	6199	BP	BP	GTO	15	2.407	248.00	6.0	6	NONE	NONE	-	-
APSTAR 7	76.5	0	5054	BP	BP	GTO	15	2.423	256.80	6.0	6	NONE	NONE	-	-
AL YAH 2 (YAHSAT 1B)	47.5	0.04	6050	BP	BP	GTO	15	2.488	365.00	6.0	6	NONE	NONE	-	-
JCSAT-4B (JCSAT-13)	124	0.1	4528	MP	BP	GTO	15	2.548	211.20	6.0	6	NONE	NONE	-	-
VINASAT 2	131.8	0.1	2969	MP	BP	GTO	15	2.548	194.00	6.0	6	NONE	NONE	-	-
TELESAT NIMIQ 6	268.9	0	4745	BP	BP	GTO	15	2.553	184.00	6.0	6	NONE	NONE	-	-
ECHOSTAR 17 (JUPITER 1)	252.9	0	6100	E	BP	GTO	15	2.688	335.00	6.0	6	NONE	NONE	-	-
METEOSAT 10 (MSG 3)	9.2	1.8	2035	BP	BP	GTO	7	2.688	395.00	2.8	6	LE	FULL SK	-	-
SES-5	5	0.1	6008	E	BP	GTO	15	2.698	351.00	6.0	6	NONE	NONE	-	-
HYLAS 2	31	0.1	3200	MP	BP	GTO	15	2.764	146.00	6.0	6	NONE	NONE	-	-
INTELSAT 20	68.5	0.1	6094	BP	BP	GTO	18	2.764	375.30	7.2	6	NONE	NONE	-	-
INTELSAT 21	302	0.1	5984	BP	BP	GTO	15	2.809	174.00	6.0	6	NONE	NONE	-	-
ASTRA 2F	28.2	0.1	5968	BP	BP	GTO	15	2.92	333.50	6.0	6	NONE	NONE	-	-
GSAT-10	83	0.2	3401	BP	BP	GTO	15	2.92	153.00	6.0	6	NONE	NONE	-	-
INTELSAT 23	307	0	2681	MP	BP	GTO	15	2.963	170.00	6.0	6	NONE	NONE	-	-
YAMAL 300K	183	0.1	1640	E	BP	GTO	14	3.016	212.00	5.6	6	MR	REFUEL SINGLE	-	-
EUTELSAT 21B (EUTELSAT 21B/W6A)	21.5	0.1	5012	BP	BP	GTO	15	3.038	250.00	6.0	6	NONE	NONE	-	-
STAR ONE C3	285	0.1	3227	MP	BP	GTO	15	3.038	198.00	6.0	6	NONE	NONE	-	-
ECHOSTAR 16	298.5	0	6650	E	BP	GTO	15	3.065	280.00	6.0	6	NONE	NONE	-	-
CHINASAT 12 (ZHONGXING 15A)	87.5	0	5054	BP	BP	GTO	15	3.084	216.00	6.0	6	NONE	NONE	-	-
EUTELSAT 70B (W5A)	70.5	0.1	5210	BP	BP	GTO	15	3.101	250.00	6.0	6	NONE	NONE	-	-
MEXSAT 3	245.2	0.1	2934	MP	BP	GTO	15	3.145	185.00	6.0	6	NONE	NONE	-	-
TDRS 11	189	6	3454	E	BP	GTO	15	3.261	497.50	6.0	6	NONE	NONE	-	-
AMAZONAS 3	299	0.1	6254	BP	BP	GTO	15	3.282	221.00	6.0	6	NONE	NONE	-	-
AZERSPACE-1/AFRICASAT 1A	46	0.1	3275	MP	BP	GTO	15	3.282	203.00	6.0	6	NONE	NONE	-	-
EUTELSAT 117 WEST A (SATMEX 8)	243.2	0	5474	BP	BP	GTO	15	3.411	190.00	6.0	6	NONE	NONE	-	-
TELESAT ANIK G1	252.7	0	4905	BP	BP	GTO	15	3.465	255.00	6.0	6	NONE	NONE	-	-
EUTELSAT 7B (EUTELSAT 3D)	7	0	5470	BP	BP	GTO	15	3.545	266.60	6.0	6	NONE	NONE	-	-
SES-6	319.5	0.1	6140	BP	BP	GTO	15	3.599	319.50	6.0	6	NONE	NONE	-	-
IRNSS-1A	55	27	1425	BP	BP	GTO	10	3.676	30.00	4.0	6	NONE	NONE	-	-
ALPHASAT I-XL	25	0	6649	BP	BP	GTO	15	3.742	813.00	6.0	6	MR	REFUEL SINGLE	-	-
INSAT 3D	82	0.2	2120	BP	MP	GTO	7	3.742	116.00	2.8	6	MR	REFUEL SINGLE	-	-

Table H-8 – Sample 1 – Population 3 (part 2)

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
ES'HAIL 1	25.5	0.1	6310	BP	BP	GTO	15	3.838	300.00	6.0	6	NONE	NONE	-	-
AMOS-4	65	0.1	4260	BP	BP	GTO	12	3.844	170.00	4.8	6	NONE	NONE	-	-
ASTRA 2E	28.2	0.1	6020	BP	BP	GTO	15	3.923	287.50	6.0	6	NONE	NONE	-	-
SIRIUS FM-6 (SIRIUS RADIO)	243.9	0.1	6018	E	BP	GTO	15	3.994	269.00	6.0	6	NONE	NONE	-	-
SES-8	95	0	3138	MP	BP	GTO	15	4.101	174.00	6.0	6	NONE	NONE	-	-
INMARSAT 5-F1 (GLOBAL XPRESS 1)	62.5	0.1	6070	BP	BP	GTO	15	4.114	357.00	6.0	6	NONE	NONE	-	-
EXPRESS AM-5	140	0	3400	E	E	GTO	15	4.163	235.00	6.0	6	MR	REFUEL SINGLE	-	-
GSAT-14	74	0.2	1982	BP	BP	GTO	12	4.191	31.50	4.8	6	NONE	NONE	-	-
THAICOM 6 (AFRICOM 1)	78.5	0.1	3325	MP	BP	GTO	15	4.195	160.00	6.0	6	NONE	NONE	-	-
TDRS 12	319	7	3454	E	BP	GTO	15	4.242	497.50	6.0	6	NONE	NONE	-	-
ABS-2	75	0.1	6330	BP	BP	GTO	15	4.279	285.00	6.0	6	NONE	NONE	-	-
TURKSAT 4A	42	0	4910	BP	BP	GTO	15	4.301	212.50	6.0	6	NONE	NONE	-	-
EXPRESS AT-1	56	0	1726	E	BP	GTO	15	4.381	94.50	6.0	6	NONE	NONE	-	-
EXPRESS AT-2	140	0.1	1426	E	BP	GTO	15	4.381	81.00	6.0	6	NONE	NONE	-	-
ASTRA 5B (HYLAS 2B)	31.5	0.1	5724	BP	BP	GTO	15	4.4	393.00	6.0	6	NONE	NONE	-	-
HISPASAT 74W-1 (AMAZONAS 4A)	286.1	0	2938	MP	BP	GTO	15	4.4	193.50	6.0	6	NONE	NONE	-	-
IRNSS-1B	55	31	1432	BP	BP	GTO	10	4.434	30.00	4.0	6	NONE	NONE	-	-
KAZSAT 3	58.5	0.1	1900	E	E	GTO	15	4.499	148.00	6.0	6	MR	REFUEL SINGLE	-	-
LUCH 5V	95	4.8	1148	E	BP	GTO	10	4.499	113.81	4.0	6	NONE	NONE	-	-
EUTELSAT 3B	3	0.1	5967	BP	BP	GTO	15	4.578	280.00	6.0	6	NONE	NONE	-	-
AMOS 7 (ASIASAT 8)	356	0.06	4535	BP	BP	GTO	15	4.771	176.60	6.0	6	NONE	NONE	-	-
ASIASAT 6/THAICOM 7	120	0.1	4428	BP	BP	GTO	15	4.861	172.40	6.0	6	NONE	NONE	-	-
MEASAT 3B	91.5	0	5897	BP	BP	GTO	15	4.874	370.00	6.0	6	NONE	NONE	-	-
OPTUS 10	164	0.1	3270	E	BP	GTO	15	4.874	210.29	6.0	6	NONE	NONE	-	-
HIMAWARI 08 (GMS 08)	140	0.08	3500	BP	BP	GTO	15	4.943	300.00	6.0	6	NONE	NONE	-	-
IRNSS-1C	83	4.8	1425	BP	BP	GTO	10	4.967	30.00	4.0	6	NONE	NONE	-	-
ARSAT 1	288.2	0	2983	BP	BP	GTO	15	4.97	195.00	6.0	6	NONE	NONE	-	-
INTELSAT 30/ISDLA-1	264.9	0.1	6320	E	BP	GTO	15	4.97	283.00	6.0	6	NONE	NONE	-	-
DIRECTV 14	261	0.1	6299	E	BP	GTO	15	5.109	371.85	6.0	6	NONE	NONE	-	-
GSAT-16	55	0.2	3182	BP	BP	GTO	12	5.109	195.63	4.8	6	MR	REFUEL SINGLE	-	-
YAMAL 401	90	0	2976	E	BP	GTO	15	5.132	315.00	6.0	6	NONE	NONE	-	-
ASTRA 2G	28.2	0.1	6022	BP	BP	GTO	15	5.167	287.50	6.0	6	NONE	NONE	-	-
INMARSAT 5-F2 (GLOBAL XPRESS 2)	305	0	6070	BP	BP	GTO	15	5.265	357.00	6.0	6	NONE	NONE	-	-
ABS-3A	357	0.07	1954	E	E	GTO	15	5.343	137.50	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 115 WEST B (SATMEX 7)	245.1	0	2205	E	E	GTO	15	5.343	137.50	6.0	6	MR	REFUEL SINGLE	-	-
EXPRESS AM-7	40	0	5720	BP	BP	GTO	15	5.389	255.00	6.0	6	NONE	NONE	-	-
IRNSS-1D	111.7	30.5	1425	BP	BP	GTO	10	5.415	30.00	4.0	6	NONE	NONE	-	-
THOR 7	359	0	4590	BP	BP	GTO	15	5.496	225.30	6.0	6	NONE	NONE	-	-
TURKMENALEM 52E/MONACOSAT	52	0	4731	BP	BP	GTO	16	5.499	215.00	6.4	6	NONE	NONE	-	-
DIRECTV 15	257.3	0.11	6205	BP	BP	GTO	15	5.581	270.00	6.0	6	NONE	NONE	-	-
SKY MEXICO-1	281.2	0.04	3182	MP	BP	GTO	15	5.581	195.00	6.0	6	NONE	NONE	-	-
METEOSAT 11 (MSG 4)	0	3.14	2043	BP	BP	GTO	7	5.714	219.00	2.8	6	LE	FULL SK	-	-
STAR ONE C4	290	0.09	5565	BP	BP	GTO	15	5.714	289.00	6.0	6	NONE	NONE	-	-
EUTELSAT 8 WEST B	352	0.08	5782	BP	BP	GTO	15	5.814	300.00	6.0	6	NONE	NONE	-	-
HISPASAT 55W-2 (INTELSAT 34)	304.5	0.04	3300	E	BP	GTO	16	5.814	195.00	6.4	6	NONE	NONE	-	-
INMARSAT 5-F3 (GLOBAL XPRESS 3)	179.7	0.06	6070	BP	BP	GTO	15	5.834	357.00	6.0	6	NONE	NONE	-	-
EXPRESS AM-8	346	0.04	2163	E	BP	GTO	15	5.882	158.00	6.0	6	NONE	NONE	-	-
ARSAT 2	279	0.02	2977	BP	BP	GTO	15	5.926	195.00	6.0	6	NONE	NONE	-	-
SKY MUSTER (NBN 1A)	140	0.03	6440	BP	BP	GTO	15	5.926	490.00	6.0	6	NONE	NONE	-	-
MORELOS 3 (MEXSAT 2)	246.9	7.1	5325	MP	BP	GTO	15	5.93	410.00	6.0	6	NONE	NONE	-	-
APSTAR 9	142	0.14	5235	BP	BP	GTO	15	5.969	194.00	6.0	6	NONE	NONE	-	-
TURKSAT 4B	50	0.02	4928	BP	BP	GTO	15	5.97	212.50	6.0	6	NONE	NONE	-	-
BADR 7 (ARABSAT 6B)	26	0.09	6100	BP	BP	GTO	15	6.038	400.00	6.0	6	NONE	NONE	-	-
GSAT-15	93.5	0.08	3165	BP	BP	GTO	12	6.038	140.00	4.8	6	NONE	NONE	-	-
LAOSAT 1	128.5	0.1	5200	BP	BP	GTO	15	6.065	205.00	6.0	6	NONE	NONE	-	-
TELSTAR 12 VANTAGE	345	0.06	4900	BP	BP	GTO	15	6.075	233.00	6.0	6	NONE	NONE	-	-
ELEKTRO-L N2	76	0.45	1797	MP	BP	GTO	10	6.122	150.00	4.0	6	MR	REFUEL SINGLE	-	-
EXPRESS AMU-1/EUTELSAT 36C	36	0.08	5720	BP	BP	GTO	15	6.159	330.00	6.0	6	NONE	NONE	-	-
GAOFEN 4	106	0.58	4600	BP	BP	GTO	8	6.169	263.77	3.2	6	MR	REFUEL SINGLE	-	-
BELINTERSAT 1 (CHINASAT 15)	51.5	0.06	5223	BP	BP	GTO	15	6.219	291.73	6.0	6	NONE	NONE	-	-
IRNSS-1E	111.8	28.06	1425	BP	BP	GTO	12	6.231	30.00	4.8	6	NONE	NONE	-	-

Table H-9 – Sample 1 – Population 3 (part 3)

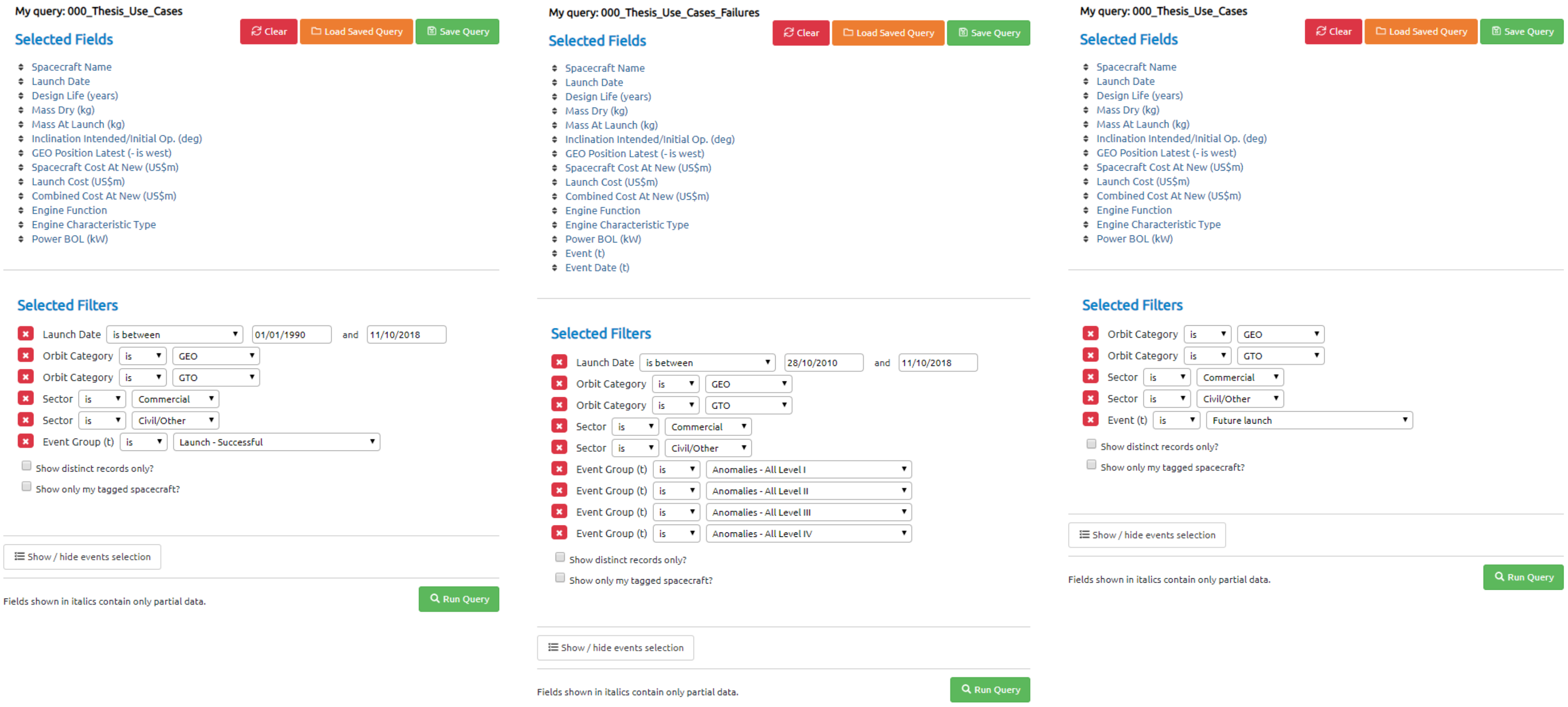
Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
INTELSAT 29e (INTELSAT EPIC 1)	310	0.12	6552	MP	BP	GTO	15	6.252	680.00	6.0	6	LE	FULL SK	-	-
EUTELSAT 9B/EDRS A	9	0.07	5162	BP	BP	GTO	15	6.258	495.00	6.0	6	MR	REFUEL SINGLE	-	-
SES-9	108.2	0.08	5271	E	BP	GTO	15	6.354	290.00	6.0	6	NONE	NONE	-	-
EUTELSAT 65 WEST A	295	0.03	6564	BP	BP	GTO	15	6.365	350.00	6.0	6	NONE	NONE	-	-
IRNSS-1F	32.5	5.09	1425	BP	BP	GTO	12	6.369	30.00	4.8	6	NONE	NONE	-	-
IRNSS-1G	129.5	5	1425	BP	BP	GTO	12	6.502	30.00	4.8	6	NONE	NONE	-	-
JCSAT-2B (JCSAT-14)	154	0.02	4696	BP	BP	GTO	15	6.524	200.00	6.0	6	NONE	NONE	-	-
THAICOM 8	78.5	0.03	3100	MP	BP	GTO	15	6.584	162.00	6.0	6	NONE	NONE	-	-
INTELSAT 31/ISDLA-2	264.9	0.13	6450	E	BP	GTO	15	6.618	218.00	6.0	6	NONE	NONE	-	-
ABS-2A (MONGOLSAT 1)	75	0.05	1944	E	E	GTO	15	6.635	137.50	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 117 WEST B (SATMEX 9)	243	0.01	2222	E	E	GTO	15	6.635	137.50	6.0	6	MR	REFUEL SINGLE	-	-
BRISAT	150.5	0.07	3540	BP	BP	GTO	15	6.644	210.00	6.0	6	NONE	NONE	-	-
ECHOSTAR 18	298.6	0.05	6300	BP	BP	GTO	15	6.644	500.00	6.0	6	LE	FULL SK	-	-
TIANTONG 1	101.4	5	5400	BP	BP	GTO	12	6.775	302.47	4.8	6	NONE	NONE	-	-
INTELSAT 36	68.5	0.12	3253	BP	BP	GTO	15	6.827	205.00	6.0	6	NONE	NONE	-	-
INSAT 3DR	74	0.13	2211	BP	BP	GTO	10	6.867	153.93	4.0	6	MR	REFUEL SINGLE	-	-
GSAT-18	74	0.09	3404	BP	BP	GTO	15	6.942	160.50	6.0	6	NONE	NONE	-	-
SKY MUSTER 2 (NBN 1B)	145	0.03	6405	BP	BP	GTO	15	6.942	490.00	6.0	6	NONE	NONE	-	-
HIMAWARI 09 (GMS 09)	141	0.07	3500	BP	BP	GTO	15	7.017	300.00	6.0	6	NONE	NONE	-	-
SHI JIAN 17	94.1	0.8	4000	BP	BP	GTO	15	7.021	231.89	6.0	6	NONE	NONE	-	-
GOES 16	285	0.01	5192	BP	BP	GTO	15	7.066	573.00	6.0	6	MR	REFUEL SINGLE	-	-
TIANLIAN-1D	76.9	3.06	2462	MP	MP	GTO	8	7.073	159.29	3.2	6	NONE	NONE	-	-
ECHOSTAR 19/JUPITER 2	262.9	0.06	6637	E	MP	GTO	15	7.145	448.00	6.0	6	MR	REFUEL SINGLE	-	-
STAR ONE D1	276	0.07	6433	BP	BP	GTO	15	7.153	400.00	6.0	6	MR	REFUEL SINGLE	-	-
HISPASAT 36W-1 (HISPASAT AG 1)	324	0.1	3343	BP	BP	GTO	15	7.255	317.00	6.0	6	MR	REFUEL SINGLE	-	-
SKY BRASIL-1/INTELSAT 32e	316.8	0.08	6300	BP	BP	GTO	15	7.304	335.00	6.0	6	MR	REFUEL SINGLE	-	-
TELKOM 3S	118	0.03	3550	BP	BP	GTO	15	7.304	274.70	6.0	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 23	315.1	0.08	5600	E	BP	GTO	15	7.384	235.00	6.0	6	MR	REFUEL SINGLE	-	-
SES-10	293	0.06	5282	BP	BP	GTO	15	7.425	255.00	6.0	6	MR	REFUEL SINGLE	-	-
SHI JIAN 13 (CHINASAT 16)	110.5	0.07	4600	E	E	GTO	15	7.459	287.53	6.0	6	MR	REFUEL SINGLE	-	-
KOREASAT 7	116	50	3680	BP	BP	GTO	17	7.521	281.00	6.8	6	MR	REFUEL SINGLE	-	-
SOUTH ASIA SATELLITE (GSAT-9)	97.3	20.57	2230	BP	BP	GTO	12	7.522	94.10	4.8	6	NONE	NONE	-	-
INMARSAT 5-F4 (GLOBAL XPRESS 4)	56.5	0.07	6086	BP	BP	GTO	15	7.551	285.00	6.0	6	MR	REFUEL SINGLE	-	-
SES-15	230.9	0.02	2302	E	E	GTO	15	7.558	230.00	6.0	6	MR	REFUEL SINGLE	-	-
QUASI ZENITH SATELLITE 2 (MICHIBIKI 2)	137	44.76	4100	BP	BP	GTO	15	7.595	265.30	6.0	6	MR	REFUEL SINGLE	-	-
EUTELSAT 172B	172	0.06	3551	BP	E	GTO	15	7.597	236.20	6.0	6	MR	REFUEL SINGLE	-	-
VIASAT-2	290.1	0.02	6418	BP	BP	GTO	14	7.597	496.00	5.6	6	NONE	NONE	-	-
GSAT-19	47.8	0.06	3136	BP	BP	GTO	10	7.607	194.21	4.0	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 21	10.3	7.48	6871	MP	MP	GTO	15	7.614	300.90	6.0	6	MR	REFUEL SINGLE	-	-
BULGARIASAT 1	1.9	0.05	3669	BP	BP	GTO	15	7.657	216.00	6.0	6	MR	REFUEL SINGLE	-	-
GSAT-17	93.5	0.09	3477	BP	BP	GTO	15	7.671	159.10	6.0	6	MR	REFUEL SINGLE	-	-
HELLAS-SAT 3/INMARSAT-S-EAN	39	0.04	5780	BP	BP	GTO	15	7.671	300.00	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 35e (INTELSAT EPIC 3)	325.5	0.09	6761	MP	BP	GTO	15	7.691	411.00	6.0	6	MR	REFUEL SINGLE	-	-
TDRS 13	311.1	7.01	3454	E	BP	GTO	15	7.81	421.40	6.0	6	MR	REFUEL SINGLE	-	-
QUASI ZENITH SATELLITE 3 (MICHIBIKI 3)	127	0.09	4700	BP	BP	GTO	15	7.812	265.30	6.0	6	MR	REFUEL SINGLE	-	-
AMAZONAS 5	299	0.07	5900	BP	BP	GTO	15	7.876	240.00	6.0	6	MR	REFUEL SINGLE	-	-
ASIASAT 9	122	0.05	6141	E	BP	GTO	15	7.923	270.00	6.0	6	MR	REFUEL SINGLE	-	-
BSAT 4A	110	0.04	3520	BP	BP	GTO	15	7.926	235.00	6.0	6	MR	REFUEL SINGLE	-	-
INTELSAT 37e (INTELSAT EPIC 4)	342	0.02	6438	MP	BP	GTO	15	7.926	435.00	6.0	6	MR	REFUEL SINGLE	-	-
QUASI ZENITH SATELLITE 4 (MICHIBIKI 4)	135	40.44	4000	BP	BP	GTO	15	7.953	265.30	6.0	6	MR	REFUEL SINGLE	-	-
ECHOSTAR 105/SES-11	255.1	0.07	5200	BP	BP	GTO	15	7.959	275.00	6.0	6	MR	REFUEL SINGLE	-	-
KOREASAT 5A	113	0.02	3700	BP	BP	GTO	17	8.011	271.00	6.8	6	MR	REFUEL SINGLE	-	-
SES-16/GOVSAT 1	21.5	0.04	4370	E	BP	GTO	15	8.266	264.69	6.0	6	MR	REFUEL SINGLE	-	-
GOES 17	270.5	0.06	5192	BP	BP	GTO	10	8.345	573.00	4.0	6	LE	FULL SK	-	-
HISPASAT 30W-6 (HISPASAT 1F)	330	0.09	6092	BP	BP	GTO	15	8.357	245.00	6.0	6	MR	REFUEL SINGLE	-	-
HYLAS 4	21.3	0.04	4050	E	BP	GTO	15	8.441	270.00	6.0	6	MR	REFUEL SINGLE	-	-
IRNSS-1I	57	28.56	1425	BP	BP	GTO	12	8.458	30.00	4.8	6	NONE	NONE	-	-
BANGABANDHU-1	119.1	0.04	3500	BP	BP	GTO	15	8.54	248.00	6.0	6	MR	REFUEL SINGLE	-	-
SES-12	95	0	5384	BP	E	GTO	15	8.604	361.00	6.0	6	MR	REFUEL SINGLE	-	-
TELSTAR 19 VANTAGE	297	0.09	7076	E	BP	GTO	15	8.735	420.69	6.0	6	MR	REFUEL SINGLE	-	-
TELSTAR 18 VANTAGE/APSTAR 5C	138	0	7070	E	E	GTO	15	8.872	186.10	6.0	6	MR	REFUEL SINGLE	-	-

Table H-10 – Sample 2

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
SGDC 1	285	0.06	5735	BP	BP	GTO	15	7.523	438.00	6.0	6	RR	NONE	2	70
AMOS 7 (ASIASAT 8)	356	0.06	4535	BP	BP	GTO	15	4.774	176.60	6.0	6	RR	NONE	5.026	50
ELEKTRO-L N1	345.5	0.4	1797	MP	BP	GTO	10	1.232	150.00	4.0	6	RR	NONE	6.711	50
LUCH 5A	167	4.9	1150	E	BP	GTO	10	2.122	113.91	4.0	6	RR	NONE	1.01	50
SES-4	338	0.1	6180	BP	BP	GTO	15	2.301	320.00	6.0	6	RR	NONE	1	50
SKYTERRA 1	258.7	6.1	5360	BP	BP	GTO	15	1.049	306.00	6.0	6	RR	NONE	1.042	50

Table H-11 – Sample 3

Name	ohm [deg.]	i [deg.]	Mass [kg]	Prop. Orb. Insert.	Prop. S.K.	Initial Orbit	Life [years]	Op. Start [year]	Cost [M$]	TTBE [years]	Disc. Rate [% per year]	App.	Type	Fail. Time [Year]	Capab. Loss [%]
ARABSAT 6A	30.5	0	7724	MP	BP	GTO	30	1.03	418.72	7.8	6	MR	PAYLOAD AUGM.	-	-
BSAT 4B	110	0	4532	BP	BP	GTO	30	2.447	252.71	7.2	6	MR	PAYLOAD AUGM.	-	-
EDRS C (HYLAS 3)	31	0	4635	BP	BP	GTO	30	1.444	257.61	7.2	6	MR	PAYLOAD AUGM.	-	-
EUTELSAT 5 WEST B	355	0	3527	E	BP	GTO	30	1.277	217.56	7.2	6	MR	PAYLOAD AUGM.	-	-
GSAT-11	74	0	7370	BP	BP	GTO	30	1	406.92	7.2	6	MR	PAYLOAD AUGM.	-	-
GSAT-30	83	0	4441	BP	BP	GTO	30	1.444	248.46	7.2	6	MR	PAYLOAD AUGM.	-	-
GSAT-31	48	0	3218	BP	BP	GTO	30	1.03	193.55	7.2	6	MR	PAYLOAD AUGM.	-	-
INSAT 3DS	74	0	2318	BP	BP	GTO	14	4.573	157.68	3.4	6	MR	PAYLOAD AUGM.	-	-
INTELSAT 39	62	0	8368	E	BP	GTO	30	1.444	497.91	7.2	6	MR	PAYLOAD AUGM.	-	-
MTG-I1	9.5	0	4154	BP	BP	GTO	17.003	3.951	238.41	4.1	6	MR	PAYLOAD AUGM.	-	-
MTG-I2	9.5	0	4154	BP	BP	GTO	17.003	7.701	238.41	4.1	6	MR	PAYLOAD AUGM.	-	-
MTG-S1	0	0	4385	BP	BP	GTO	17.003	1.57	249.34	4.1	6	MR	PAYLOAD AUGM.	-	-
SKY MEXICO-2	283.8	0	3862	MP	BP	GTO	30	1.57	216.21	7.2	6	MR	PAYLOAD AUGM.	-	-
TURKSAT 5A	31	0	3649	BP	E	GTO	30	2.573	227.96	7.2	6	MR	PAYLOAD AUGM.	-	-
YAMAL 601	49	0	7338	BP	BP	GTO	30	1.2	404.90	7.2	6	MR	PAYLOAD AUGM.	-	-



My query: 000_Thesis_Use_Cases

Selected Fields

- Spacecraft Name
- Launch Date
- Design Life (years)
- Mass Dry (kg)
- Mass At Launch (kg)
- Inclination Intended/Initial Op. (deg)
- GEO Position Latest (- is west)
- Spacecraft Cost At New (US$m)
- Launch Cost (US$m)
- Combined Cost At New (US$m)
- Engine Function
- Engine Characteristic Type
- Power BOL (kW)

Selected Filters

Launch Date is between 01/01/1990 and 11/10/2018
Orbit Category is GEO
Orbit Category is GTO
Sector is Commercial
Sector is Civil/Other
Event Group (t) is Launch - Successful

☐ Show distinct records only?
☐ Show only my tagged spacecraft?

Fields shown in italics contain only partial data.

(a)

My query: 000_Thesis_Use_Cases_Failures

Selected Fields

- Spacecraft Name
- Launch Date
- Design Life (years)
- Mass Dry (kg)
- Mass At Launch (kg)
- Inclination Intended/Initial Op. (deg)
- GEO Position Latest (- is west)
- Spacecraft Cost At New (US$m)
- Launch Cost (US$m)
- Combined Cost At New (US$m)
- Engine Function
- Engine Characteristic Type
- Power BOL (kW)
- Event (t)
- Event Date (t)

Selected Filters

Launch Date is between 28/10/2010 and 11/10/2018
Orbit Category is GEO
Orbit Category is GTO
Sector is Commercial
Sector is Civil/Other
Event Group (t) is Anomalies - All Level I
Event Group (t) is Anomalies - All Level II
Event Group (t) is Anomalies - All Level III
Event Group (t) is Anomalies - All Level IV

☐ Show distinct records only?
☐ Show only my tagged spacecraft?

Fields shown in italics contain only partial data.

(b)

My query: 000_Thesis_Use_Cases

Selected Fields

- Spacecraft Name
- Launch Date
- Design Life (years)
- Mass Dry (kg)
- Mass At Launch (kg)
- Inclination Intended/Initial Op. (deg)
- GEO Position Latest (- is west)
- Spacecraft Cost At New (US$m)
- Launch Cost (US$m)
- Combined Cost At New (US$m)
- Engine Function
- Engine Characteristic Type
- Power BOL (kW)

Selected Filters

Orbit Category is GEO
Orbit Category is GTO
Sector is Commercial
Sector is Civil/Other
Event (t) is Future launch

☐ Show distinct records only?
☐ Show only my tagged spacecraft?

Fields shown in italics contain only partial data.

(c)

Figure H-1 – SpaceTrak query parameters – (a) Sample 1, (b) Sample 2, (c) Sample 3

H.2 Servicing Tickets

The information provided by the framework about the servicing tickets can be used to closely track characteristics of the servicing operations such as position of Client and Servicer, when servicing was requested and assigned, the time and resources spent. Such information can be used in a detailed analysis of servicing as presented in the use cases of Chapter 7. The following tables present the results as they are generated by the framework.

Table H-12 – Servicing Tickets Data – Use Case 1 (Population 1)

ID	Client ID	Client State	Client ohm [rad]	Client i [rad]	Servicer ID	Servicer ohm [rad]	Servicer i [rad]	ΔV Servicing [km/s]	Ticket Open [Year]	Ticket Assign [Year]	Ticket Servicing [Year]	Ticket Close [Year]	Priority	Waiting Time [Years]	Propellant Mass Spent [kg]
1	13	OPERATIONAL	0.230	0.002	2	0.230	0.002	0.002	4.545	4.545	4.674	4.737	NORMAL	0.000	28.583
2	15	OPERATIONAL	1.082	0.017	2	0.230	0.002	0.106	4.679	4.737	4.865	4.929	NORMAL	0.058	28.702
3	2	OPERATIONAL-OLD	1.257	0.052	1	1.257	0.052	0.002	4.929	4.929	5.057	7.518	NORMAL	0.000	34.654
4	3	OPERATIONAL	1.187	0.003	2	1.082	0.017	0.089	5.351	5.351	5.479	5.542	NORMAL	0.000	38.851
5	6	OPERATIONAL	1.920	0.003	2	1.187	0.003	0.008	5.562	5.562	5.690	5.753	NORMAL	0.000	27.213
6	22	OPERATIONAL	1.920	0.003	2	1.920	0.003	0.002	6.559	6.559	6.687	6.751	NORMAL	0.000	26.255
7	28	OPERATIONAL	1.431	0.002	2	2.827	0.002	0.013	7.058	7.249	7.378	7.441	NORMAL	0.192	29.177
8	29	OPERATIONAL	2.827	0.002	2	1.920	0.003	0.020	7.058	7.058	7.186	7.249	NORMAL	0.000	55.108
9	12	OPERATIONAL	0.838	0.002	2	1.431	0.002	0.007	7.345	7.441	7.570	7.633	NORMAL	0.096	50.249
10	48	OPERATIONAL	1.169	0.021	2	0.838	0.002	0.123	7.403	7.633	7.761	7.825	NORMAL	0.230	30.117
11	34	OPERATIONAL	0.820	0.003	2	3.316	0.000	0.044	7.441	8.036	8.165	8.227	NORMAL	0.595	46.197
12	4	OPERATIONAL	0.663	0.002	2	0.820	0.003	0.014	7.575	8.227	8.356	8.419	NORMAL	0.652	42.689
13	8	OPERATIONAL	4.869	0.002	2	0.663	0.002	0.019	7.786	8.419	8.549	8.611	NORMAL	0.633	73.821
14	41	OPERATIONAL	2.758	0.002	2	4.869	0.002	0.019	7.825	8.611	8.740	8.803	NORMAL	0.786	60.008
15	10	OPERATIONAL	4.451	0.000	2	2.758	0.002	0.027	7.901	8.803	8.930	8.995	NORMAL	0.901	45.263
16	18	OPERATIONAL	3.002	0.000	2	4.451	0.000	0.014	8.285	8.995	9.124	9.186	NORMAL	0.710	42.550
18	46	OPERATIONAL	1.632	0.003	2	3.002	0.000	0.035	8.477	9.186	9.315	9.378	NORMAL	0.710	44.106
20	20	OPERATIONAL	3.351	0.002	2	1.632	0.003	0.027	8.592	9.378	9.506	9.570	NORMAL	0.786	71.312
21	33	OPERATIONAL	6.056	0.002	2	3.351	0.002	0.024	8.841	9.570	9.697	9.762	NORMAL	0.729	52.108
22	72	OPERATIONAL	2.793	0.003	2	6.056	0.002	0.039	8.899	9.762	9.892	9.953	NORMAL	0.863	36.781
23	25	OPERATIONAL	0.375	0.002	2	2.793	0.003	0.032	8.937	9.953	10.083	10.145	NORMAL	1.016	57.741
25	27	OPERATIONAL	0.052	0.000	2	0.375	0.002	0.015	8.975	10.145	10.274	10.337	NORMAL	1.170	66.509
27	11	OPERATIONAL	5.620	0.002	2	0.820	0.000	0.025	9.301	10.529	10.658	10.721	NORMAL	1.227	46.190
28	31	OPERATIONAL	0.820	0.000	2	0.052	0.000	0.008	9.301	10.337	10.465	10.529	NORMAL	1.036	65.684
29	108	OPERATIONAL-OLD	5.236	0.009	1	1.257	0.052	0.289	9.321	9.321	9.450	10.452	NORMAL	0.000	22.426
30	54	OPERATIONAL	1.920	0.003	2	5.620	0.002	0.042	9.436	10.721	10.851	10.912	NORMAL	1.285	32.947
31	32	OPERATIONAL	5.908	0.002	2	1.920	0.003	0.031	9.455	10.912	11.042	11.104	NORMAL	1.458	69.948
32	37	OPERATIONAL	6.144	0.000	2	5.908	0.002	0.015	9.704	11.104	11.232	11.296	NORMAL	1.400	63.668
33	39	OPERATIONAL	0.681	0.002	2	6.144	0.000	0.056	9.800	11.296	11.427	11.488	NORMAL	1.496	46.745
34	50	OPERATIONAL-OLD	4.590	0.002	1	5.236	0.009	0.050	9.973	10.452	10.581	13.597	NORMAL	0.479	24.023
35	42	OPERATIONAL	5.480	0.002	2	3.316	0.000	0.031	10.049	11.699	11.826	11.890	NORMAL	1.649	72.898
36	98	DEAD	0.279	0.002	1	4.590	0.002	0.037	10.107	13.597		13.636	NORMAL	3.490	
38	74	OPERATIONAL-OLD	1.475	0.005	1	0.279	0.002	0.033	10.548	13.636	13.764	15.764	NORMAL	3.088	12.708
39	45	OPERATIONAL	5.760	0.000	2	5.480	0.002	0.015	10.567	11.890	12.019	12.082	NORMAL	1.323	64.786
41	82	OPERATIONAL	0.820	0.003	2	5.760	0.000	0.063	10.836	12.082	12.213	12.274	NORMAL	1.247	52.673
42	36	OPERATIONAL	3.927	0.002	2	0.820	0.003	0.038	11.085	12.274	12.404	12.466	NORMAL	1.189	34.986
43	38	OPERATIONAL	4.904	0.002	2	3.927	0.002	0.010	11.104	12.466	12.594	12.658	NORMAL	1.362	30.272
44	115	DEAD	0.995	0.031	2	4.904	0.002	0.216	11.181	12.658		12.696	NORMAL	1.477	
45	58	OPERATIONAL	0.541	0.002	2	3.316	0.000	0.035	11.622	12.907	13.037	13.099	NORMAL	1.285	56.013
47	105	OPERATIONAL-OLD	5.768	0.002	1	1.475	0.005	0.040	12.178	15.764	15.894	17.912	NORMAL	3.586	16.278
48	77	OPERATIONAL	2.304	0.000	2	0.541	0.002	0.027	12.677	13.099	13.226	13.290	NORMAL	0.422	102.189
49	69	OPERATIONAL	0.262	0.000	2	2.304	0.000	0.019	12.945	13.290	13.420	13.482	NORMAL	0.345	61.425
50	103	OPERATIONAL-OLD	5.027	0.002	1	5.768	0.002	0.008	13.099	17.912	18.041	21.403	NORMAL	4.814	18.423
51	83	OPERATIONAL	0.052	0.002	2	2.374	0.000	0.031	13.118	13.674	13.803	13.866	NORMAL	0.556	71.473
52	89	OPERATIONAL	2.374	0.000	2	0.262	0.000	0.019	13.118	13.482	13.610	13.674	NORMAL	0.364	101.159
53	97	OPERATIONAL	0.541	0.000	2	0.052	0.002	0.017	13.540	13.866	13.994	14.058	NORMAL	0.326	52.880
54	99	OPERATIONAL	6.144	0.000	2	0.541	0.000	0.008	13.616	14.058	14.186	14.249	NORMAL	0.441	65.882
55	68	SCHEDULED	5.096	0.002	2	6.144	0.000	0.021	13.655	14.249	14.378	14.326	NORMAL	0.595	

Table H-13 – Servicing Tickets Data – Use Case 1 (Population 2)

ID	Client ID	Client State	Client ohm [rad]	Client i [rad]	Servicer ID	Servicer ohm [rad]	Servicer i [rad]	ΔV Servicing [km/s]	Ticket Open [Year]	Ticket Assign [Year]	Ticket Servicing [Year]	Ticket Close [Year]	Priority	Waiting Time [Years]	Propellant Mass Spent [kg]
1	16	OPERATIONAL-OLD	5.236	0.005	1	5.236	0.005	0.002	3.318	3.318	3.446	4.449	NORMAL	0.000	6.937
2	12	OPERATIONAL-OLD	5.086	0.002	1	5.236	0.005	0.025	3.989	4.449	4.578	5.945	NORMAL	0.460	19.637
3	20	OPERATIONAL-OLD	1.632	0.003	1	5.086	0.002	0.041	4.814	5.945	6.075	7.479	NORMAL	1.132	12.455
4	35	OPERATIONAL-OLD	0.724	0.035	1	1.632	0.003	0.203	5.408	7.479	7.608	9.014	NORMAL	2.071	20.105
5	37	OPERATIONAL	1.274	0.008	2	1.274	0.008	0.002	6.866	6.866	6.994	7.058	NORMAL	0.000	22.284
6	47	OPERATIONAL	0.838	0.001	2	1.274	0.008	0.052	7.499	7.499	7.627	7.690	NORMAL	0.000	46.777
8	92	OPERATIONAL-OLD	0.058	0.031	1	0.724	0.035	0.029	8.726	9.014	9.142	10.548	NORMAL	0.288	10.324
9	31	OPERATIONAL	2.374	0.002	2	0.838	0.001	0.020	8.764	8.764	8.892	8.956	NORMAL	0.000	42.672
10	10	OPERATIONAL	0.576	0.002	2	2.374	0.002	0.017	8.841	8.956	9.085	9.148	NORMAL	0.115	102.990
11	69	OPERATIONAL	1.292	0.000	2	0.576	0.002	0.019	8.879	9.148	9.276	9.340	NORMAL	0.268	43.374
12	23	OPERATIONAL	1.623	0.000	2	1.292	0.000	0.005	9.205	9.340	9.468	9.532	NORMAL	0.134	82.441
13	18	OPERATIONAL	6.065	0.000	2	1.623	0.000	0.017	9.397	9.532	9.661	9.723	NORMAL	0.134	109.612
14	130	OPERATIONAL-OLD	2.496	0.000	1	0.058	0.031	0.215	9.896	10.548	10.675	11.679	NORMAL	0.652	20.914
15	32	OPERATIONAL	1.227	0.002	2	6.065	0.000	0.051	10.299	10.299	10.429	10.490	NORMAL	0.000	140.422
16	95	OPERATIONAL-OLD	2.531	0.002	1	2.496	0.000	0.013	10.395	11.679	11.808	13.808	NORMAL	1.285	20.814
17	39	OPERATIONAL	0.576	0.002	2	1.227	0.002	0.007	10.548	10.548	10.677	10.740	NORMAL	0.000	108.953
18	99	OPERATIONAL-OLD	5.236	0.009	1	2.531	0.002	0.067	10.663	13.808	13.936	15.937	NORMAL	3.145	18.756
19	45	OPERATIONAL	1.632	0.002	2	0.576	0.002	0.011	10.932	10.932	11.060	11.123	NORMAL	0.000	102.151
20	114	OPERATIONAL-OLD	2.566	0.002	1	5.236	0.009	0.066	11.219	15.937	16.067	16.800	NORMAL	4.718	11.618
21	42	OPERATIONAL	5.794	0.002	2	1.632	0.002	0.019	11.353	11.353	11.483	11.545	NORMAL	0.000	111.291
24	58	OPERATIONAL	6.213	0.002	2	5.794	0.002	0.005	11.641	11.641	11.769	11.833	NORMAL	0.000	47.318
27	91	OPERATIONAL	1.449	0.002	2	3.316	0.000	0.028	13.636	13.636	13.765	13.827	NORMAL	0.000	109.696
28	97	OPERATIONAL	2.304	0.000	2	1.449	0.002	0.020	13.942	13.942	14.071	14.134	NORMAL	0.000	127.176
30	112	OPERATIONAL	4.344	0.002	2	2.304	0.000	0.030	14.595	14.595	14.722	14.786	NORMAL	0.000	165.927
31	115	OPERATIONAL	1.941	0.002	2	4.344	0.002	0.021	14.863	14.863	14.993	15.055	NORMAL	0.000	106.233
33	87	OPERATIONAL	3.960	0.002	2	1.941	0.002	0.019	15.553	15.553	15.681	15.745	NORMAL	0.000	72.286
34	90	OPERATIONAL	2.740	0.000	2	3.960	0.002	0.023	15.630	15.745	15.874	15.937	NORMAL	0.115	70.697
35	158	OPERATIONAL	4.451	0.007	2	2.740	0.000	0.059	15.745	15.937	16.065	16.129	NORMAL	0.192	100.677
36	121	OPERATIONAL	1.920	0.002	2	4.451	0.007	0.055	15.975	16.129	16.258	16.321	NORMAL	0.153	66.978
37	173	OPERATIONAL	3.927	0.007	2	1.920	0.002	0.051	16.436	16.436	16.563	16.627	NORMAL	0.000	100.174

Table H-14 – Servicing Tickets Data – Use Case 1 (Population 3)

ID	Client ID	Client State	Client ohm [rad]	Client i [rad]	Servicer ID	Servicer ohm [rad]	Servicer i [rad]	ΔV Servicing [km/s]	Ticket Open [Year]	Ticket Assign [Year]	Ticket Servicing [Year]	Ticket Close [Year]	Priority	Waiting Time [Years]	Propellant Mass Spent [kg]
1	15	OPERATIONAL-OLD	1.449	0.002	1	1.449	0.002	0.002	4.219	4.219	4.348	5.753	NORMAL	0.000	7.662
2	37	OPERATIONAL-OLD	0.161	0.031	1	1.449	0.002	0.195	5.197	5.753	5.882	7.997	NORMAL	0.556	24.537
3	8	OPERATIONAL	6.030	0.007	2	6.030	0.007	0.002	7.230	7.230	7.359	7.422	NORMAL	0.000	43.242
4	61	OPERATIONAL	1.431	0.003	2	6.030	0.007	0.060	7.652	7.652	7.783	7.844	NORMAL	0.000	69.482
5	103	OPERATIONAL-OLD	0.000	0.055	1	0.161	0.031	0.147	8.227	8.227	8.356	10.471	NORMAL	0.000	21.586
6	13	OPERATIONAL	1.510	0.002	2	1.431	0.003	0.013	9.301	9.301	9.430	9.493	NORMAL	0.000	64.882
7	1	OPERATIONAL	1.920	0.000	2	1.510	0.002	0.016	10.510	10.510	10.638	10.701	NORMAL	0.000	72.792
8	120	OPERATIONAL	1.850	0.010	2	1.920	0.000	0.065	10.778	10.778	10.907	10.970	NORMAL	0.000	117.263
9	10	OPERATIONAL	0.576	0.002	2	1.850	0.010	0.064	10.989	10.989	11.118	11.181	NORMAL	0.000	111.105
10	176	OPERATIONAL-OLD	4.721	0.001	1	0.000	0.055	0.345	11.353	11.353	11.483	13.501	NORMAL	0.000	41.519
11	45	OPERATIONAL	3.194	0.002	2	3.316	0.000	0.014	11.833	11.833	11.961	12.025	NORMAL	0.000	89.318
12	118	OPERATIONAL	1.326	0.008	2	3.194	0.002	0.055	12.140	12.140	12.269	12.332	NORMAL	0.000	50.981
13	91	OPERATIONAL	0.960	0.003	2	1.326	0.008	0.032	12.523	12.523	12.652	12.715	NORMAL	0.000	112.911
14	123	OPERATIONAL-OLD	5.411	0.002	1	4.721	0.001	0.014	12.753	13.501	13.630	15.899	NORMAL	0.748	25.576
15	138	OPERATIONAL	1.292	0.002	2	0.960	0.003	0.012	12.868	12.868	12.997	13.060	NORMAL	0.000	65.591
16	135	OPERATIONAL-OLD	5.212	0.001	1	5.411	0.002	0.011	13.156	15.899	16.027	16.992	NORMAL	2.742	11.788
17	60	OPERATIONAL	0.436	0.000	2	1.292	0.002	0.023	13.252	13.252	13.381	13.444	NORMAL	0.000	278.271
18	160	OPERATIONAL	0.834	0.001	2	0.436	0.000	0.012	13.616	13.616	13.745	13.808	NORMAL	0.000	92.043
23	124	OPERATIONAL	0.157	0.001	2	0.834	0.001	0.009	15.764	15.764	15.893	15.956	NORMAL	0.000	214.695
26	143	OPERATIONAL	4.974	0.000	2	0.157	0.001	0.020	16.570	16.570	16.699	16.762	NORMAL	0.000	120.241

Table H-15 – Servicing Tickets Data – Use Case 2

ID	Client ID	Client State	Client ohm [rad]	Client i [rad]	Servicer ID	Servicer ohm [rad]	Servicer i [rad]	ΔV Servicing [km/s]	Ticket Open [Year]	Ticket Assign [Year]	Ticket Servicing [Year]	Ticket Close [Year]	Priority	Waiting Time [Years]	Propellant Mass Spent [kg]
1	5	OPERATIONAL-OLD	1.449	0.002	1	1.449	0.002	0.002	3.529	3.529	3.657	5.408	NORMAL	0.000	9.590
2	6	OPERATIONAL-OLD	0.161	0.031	1	1.449	0.002	0.195	5.197	5.408	5.537	7.652	NORMAL	0.211	24.548
3	11	OPERATIONAL-OLD	0.000	0.055	1	0.161	0.031	0.147	8.227	8.227	8.356	10.471	NORMAL	0.000	21.546
4	2	OPERATIONAL	6.030	0.007	2	6.030	0.007	0.002	8.247	8.247	8.375	8.438	NORMAL	0.000	86.911
5	9	OPERATIONAL	1.431	0.003	2	6.030	0.007	0.060	8.342	8.438	8.569	8.630	NORMAL	0.096	108.879
6	20	OPERATIONAL-OLD	4.721	0.001	1	0.000	0.055	0.345	10.356	10.471	10.600	12.619	NORMAL	0.115	41.764
7	4	OPERATIONAL	1.510	0.002	2	3.316	0.000	0.027	10.529	10.529	10.658	10.721	NORMAL	0.000	65.787
8	13	OPERATIONAL	1.850	0.010	2	1.510	0.002	0.056	11.584	11.584	11.712	11.775	NORMAL	0.000	226.452
9	1	OPERATIONAL	1.920	0.000	2	1.850	0.010	0.065	12.005	12.005	12.134	12.197	NORMAL	0.000	151.730
10	14	OPERATIONAL-OLD	5.411	0.002	1	4.721	0.001	0.014	12.005	12.619	12.747	15.016	NORMAL	0.614	25.848
11	3	OPERATIONAL	0.576	0.002	2	1.920	0.000	0.024	12.485	12.485	12.614	12.677	NORMAL	0.000	211.180
12	12	OPERATIONAL	1.326	0.008	2	0.576	0.002	0.046	13.137	13.137	13.265	13.329	NORMAL	0.000	91.985
13	7	OPERATIONAL	3.194	0.002	2	3.316	0.000	0.014	13.233	13.540	13.668	13.732	NORMAL	0.307	86.848
14	10	OPERATIONAL	0.960	0.003	2	3.194	0.002	0.031	13.712	13.732	13.861	13.923	NORMAL	0.019	110.674
15	17	OPERATIONAL	1.292	0.002	2	0.960	0.003	0.012	13.885	13.923	14.052	14.115	NORMAL	0.038	130.529
16	19	OPERATIONAL	0.834	0.001	2	1.292	0.002	0.013	14.614	14.614	14.742	14.805	NORMAL	0.000	184.642
17	16	OPERATIONAL-OLD	5.212	0.001	1	5.411	0.002	0.011	14.652	15.016	15.145	16.033	NORMAL	0.364	10.967
18	8	OPERATIONAL	0.436	0.000	2	0.834	0.001	0.012	14.748	14.805	14.934	14.997	NORMAL	0.058	498.924
19	18	OPERATIONAL	4.974	0.000	2	3.316	0.000	0.017	16.570	16.570	16.698	16.762	NORMAL	0.000	449.336
20	15	OPERATIONAL	0.157	0.001	2	4.974	0.000	0.047	17.260	17.260	17.391	17.452	NORMAL	0.000	214.409

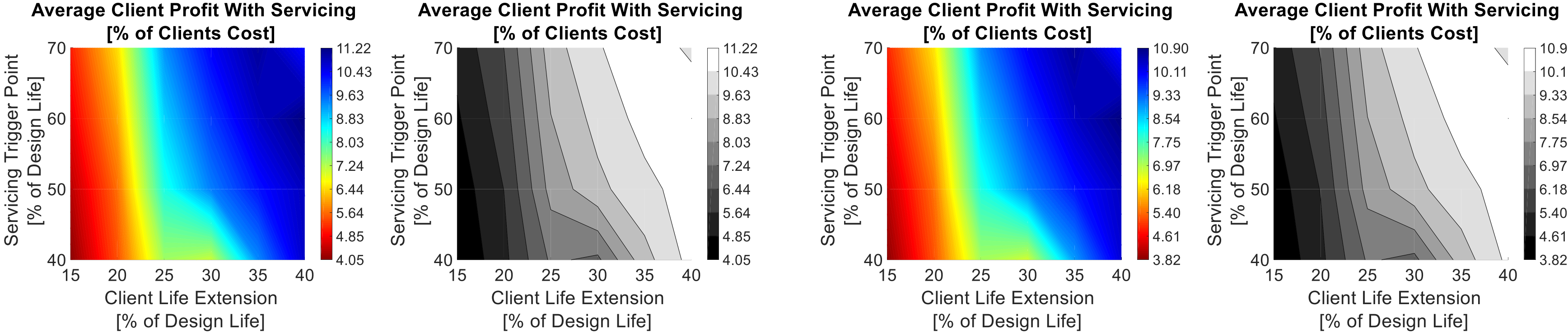
Table H-16 – Servicing Tickets Data – Use Case 3

ID	Client ID	Client State	Client ohm [rad]	Client i [rad]	Servicer ID	Servicer ohm [rad]	Servicer i [rad]	ΔV Servicing [km/s]	Ticket Open [Year]	Ticket Assign [Year]	Ticket Servicing [Year]	Ticket Close [Year]	Priority	Waiting Time [Years]	Propellant Mass Spent [kg]
4	5	OPERATIONAL-OLD	1.449	0.002	1	1.449	0.002	0.002	3.529	3.529	3.657	5.408	NORMAL	0.000	9.590
5	6	OPERATIONAL-OLD	0.161	0.031	1	1.449	0.002	0.195	5.197	5.408	5.537	7.652	NORMAL	0.211	24.548
7	11	OPERATIONAL-OLD	0.000	0.055	1	0.161	0.031	0.147	8.227	8.227	8.356	10.471	NORMAL	0.000	21.546
8	2	OPERATIONAL	6.030	0.007	2	6.030	0.007	0.002	8.247	8.247	8.375	8.438	NORMAL	0.000	86.911
9	9	OPERATIONAL	1.431	0.003	2	6.030	0.007	0.060	8.342	8.438	8.569	8.630	NORMAL	0.096	108.879
10	21	OPERATIONAL	4.974	0.001	2	3.316	0.000	0.022	8.534	8.860	8.988	9.071	HIGH	0.326	3.350
11	22	OPERATIONAL	6.213	0.001	2	4.974	0.001	0.012	8.803	9.071	9.199	9.282	HIGH	0.268	1.845
12	20	OPERATIONAL-OLD	4.721	0.001	1	0.000	0.055	0.345	10.356	10.471	10.600	12.619	NORMAL	0.115	41.764
13	4	OPERATIONAL	1.510	0.002	2	6.213	0.001	0.044	10.529	10.529	10.659	10.721	NORMAL	0.000	68.288
14	13	OPERATIONAL	1.850	0.010	2	1.510	0.002	0.056	11.584	11.584	11.712	11.775	NORMAL	0.000	226.439
15	1	OPERATIONAL	1.920	0.000	2	1.850	0.010	0.065	12.005	12.005	12.134	12.197	NORMAL	0.000	151.715
16	14	OPERATIONAL-OLD	5.411	0.002	1	4.721	0.001	0.014	12.005	12.619	12.747	15.016	NORMAL	0.614	25.848
17	3	OPERATIONAL	0.576	0.002	2	1.920	0.000	0.024	12.485	12.485	12.614	12.677	NORMAL	0.000	211.174
18	12	OPERATIONAL	1.326	0.008	2	0.576	0.002	0.046	13.137	13.137	13.265	13.329	NORMAL	0.000	91.974
19	7	OPERATIONAL	3.194	0.002	2	3.316	0.000	0.014	13.233	13.540	13.668	13.732	NORMAL	0.307	86.848
20	10	OPERATIONAL	0.960	0.003	2	3.194	0.002	0.031	13.712	13.732	13.861	13.923	NORMAL	0.019	110.674
21	17	OPERATIONAL	1.292	0.0023	2	0.9599	0.0035	0.012	13.885	13.923	14.0516	14.115	NORMAL	0.0384	130.528641
22	19	OPERATIONAL	0.834	0.001	2	1.2915	0.0023	0.013	14.614	14.614	14.7424	14.805	NORMAL	0	184.641876
23	16	OPERATIONAL-OLD	5.212	0.0009	1	5.4105	0.0021	0.011	14.652	15.016	15.145	16.033	NORMAL	0.3644	10.9667597
24	8	OPERATIONAL	0.436	0	2	0.8343	0.001	0.012	14.748	14.805	14.9341	14.997	NORMAL	0.0575	498.924042
25	18	OPERATIONAL	4.974	0.0002	2	3.3161	0	0.017	16.57	16.57	16.6976	16.762	NORMAL	0	449.335846
26	15	OPERATIONAL	0.157	0.0012	2	4.9742	0.0002	0.047	17.26	17.26	17.3908	17.452	NORMAL	0	214.40921

Table H-17 – Servicing Tickets Data – Use Case 4

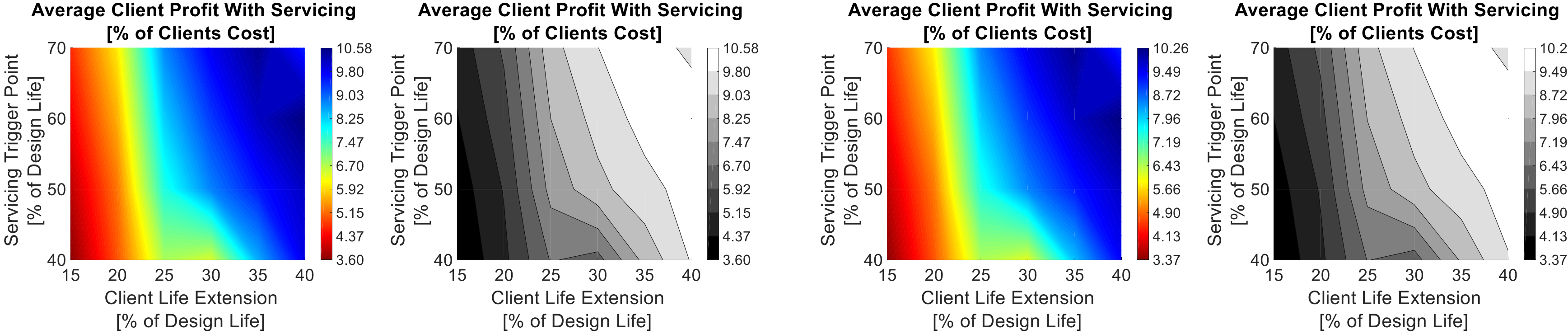
ID	Client ID	Client State	Client ohm [rad]	Client i [rad]	Servicer ID	Servicer ohm [rad]	Servicer i [rad]	ΔV Servicing [km/s]	Ticket Open [Year]	Ticket Assign [Year]	Ticket Servicing [Year]	Ticket Close [Year]	Priority	Waiting Time [Years]	Propellant Mass Spent [kg]
1	12	OPERATIONAL	0.000	0.000	1	0.000	0.000	0.002	11.795	11.795	11.923	11.967	NORMAL	0.000	0.367
2	8	OPERATIONAL	1.292	0.000	1	0.000	0.000	0.013	12.811	12.811	12.939	12.984	NORMAL	0.000	2.205
3	10	OPERATIONAL	0.166	0.000	1	1.292	0.000	0.011	14.173	14.173	14.302	14.345	NORMAL	0.000	1.859
4	11	OPERATIONAL	0.166	0.000	1	0.166	0.000	0.002	17.932	17.932	18.060	18.104	NORMAL	0.000	0.315
5	5	OPERATIONAL	1.292	0.000	1	0.166	0.000	0.011	19.792	19.792	19.920	19.964	NORMAL	0.000	1.674
6	1	OPERATIONAL	0.532	0.000	1	0.838	0.000	0.004	19.830	20.137	20.266	20.310	NORMAL	0.307	0.600
7	7	OPERATIONAL	0.838	0.000	1	1.292	0.000	0.006	19.830	19.964	20.093	20.137	NORMAL	0.134	0.806
8	15	OPERATIONAL	0.855	0.000	1	0.532	0.000	0.005	20.003	20.310	20.438	20.482	NORMAL	0.307	0.585
9	4	OPERATIONAL	6.196	0.000	1	0.855	0.000	0.010	20.079	20.482	20.611	20.655	NORMAL	0.403	1.143
12	9	OPERATIONAL	1.082	0.000	1	6.196	0.000	0.043	20.233	20.655	20.785	20.827	NORMAL	0.422	4.742

Appendix I – Solution Exploration Results – Use Case 2



(a) 80% Servicer intended profit

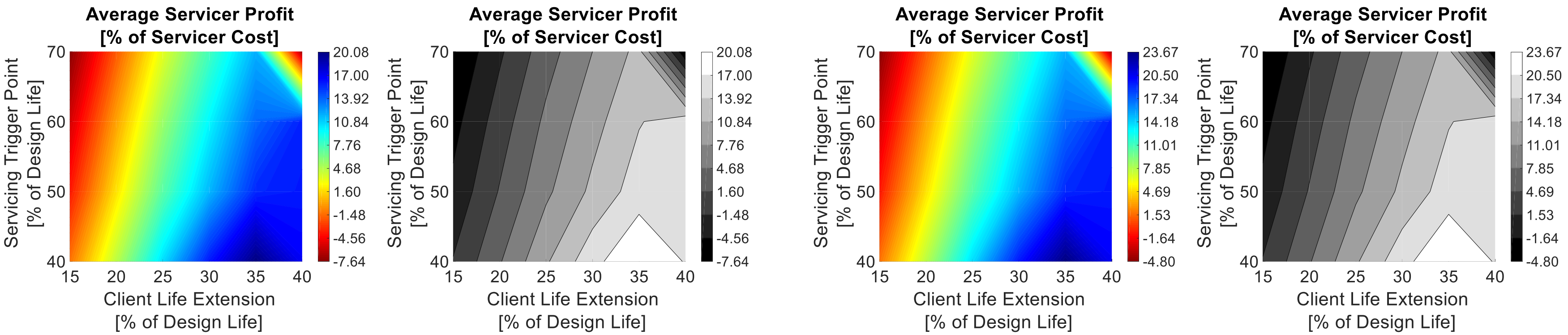
(b) 85% Servicer intended profit



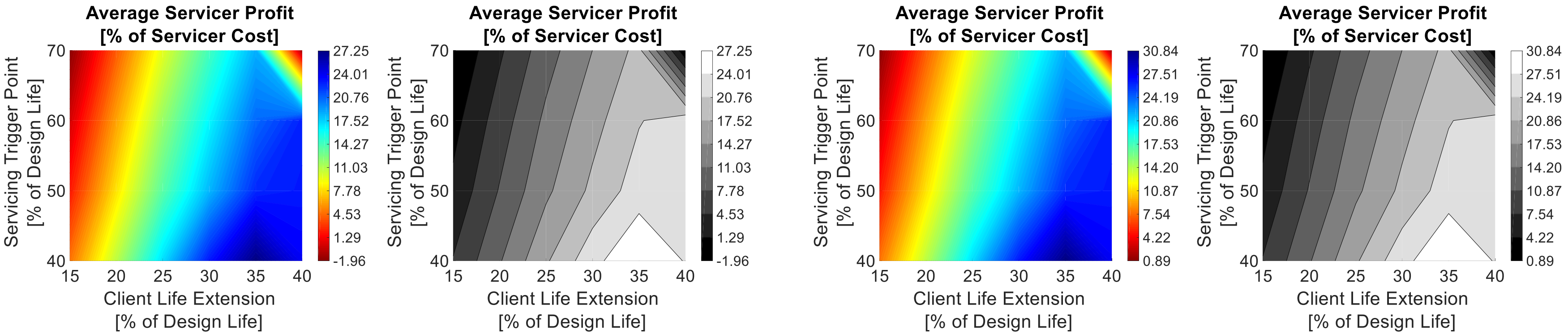
(c) 90% Servicer intended profit

(d) 95% Servicer intended profit

Figure I-1 – Solution Exploration Results – Lifetime Extension – Average Client Profit (Additional profit above that achieved without servicing)

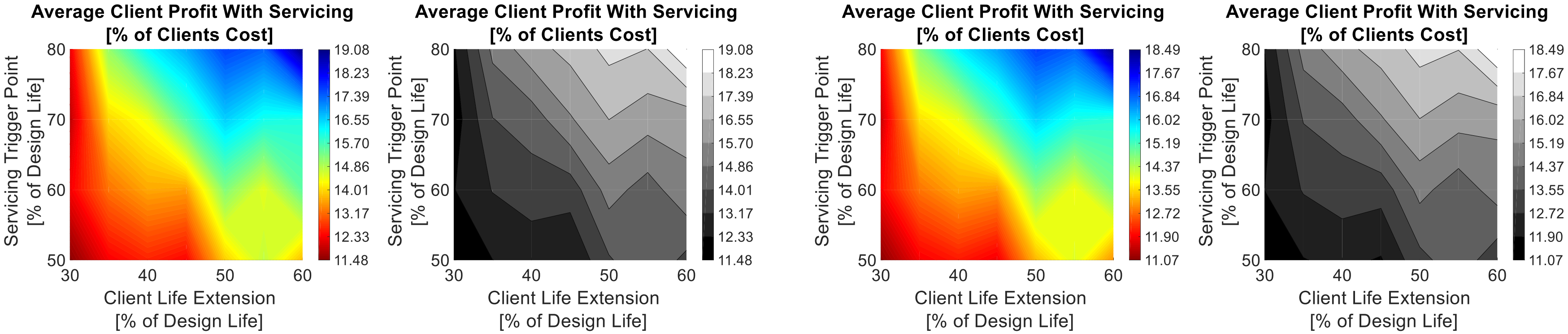


(a) 80% Servicer intended profit (b) 85% Servicer intended profit



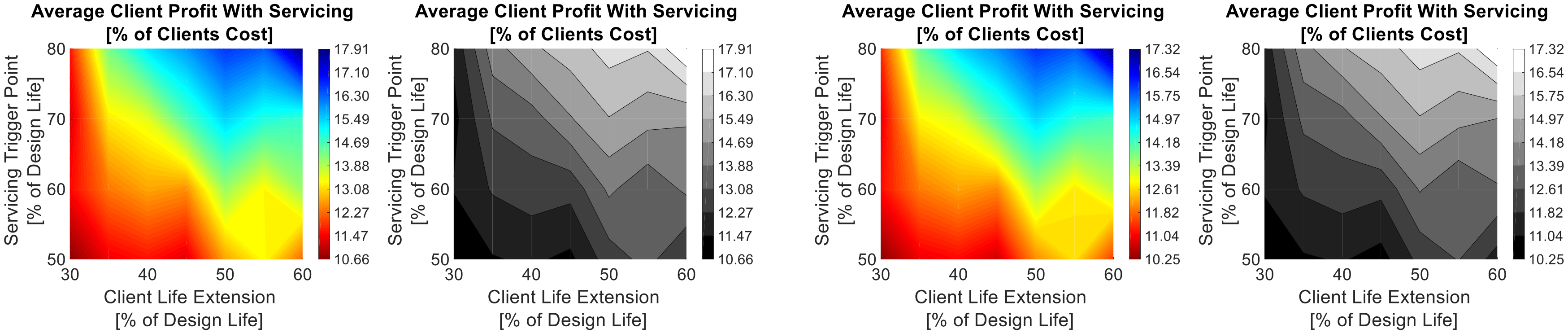
(c) 90% Servicer intended profit (d) 95% Servicer intended profit

Figure I-2 – Solution Exploration Results – Lifetime Extension – Average Servicer Profit



(a) 40% Servicer intended profit

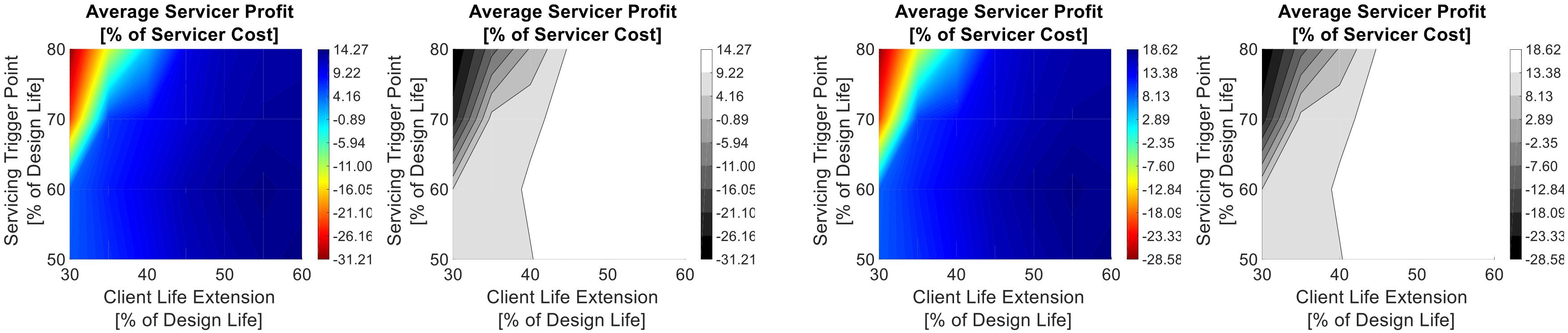
(b) 45% Servicer intended profit



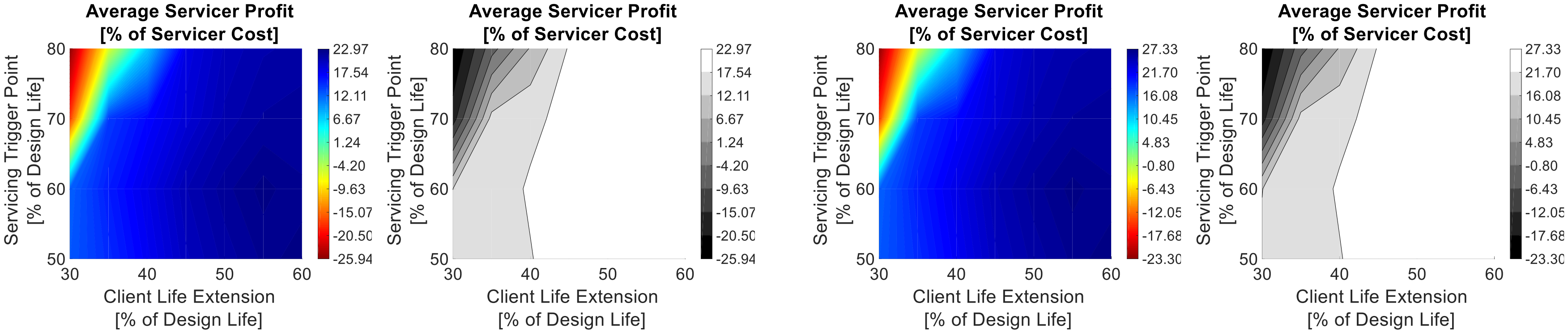
(c) 50% Servicer intended profit

(d) 55% Servicer intended profit

Figure I-3 – Solution Exploration Results – Maintenance and Repair – Average Client Profit (Additional profit above that achieved without servicing)

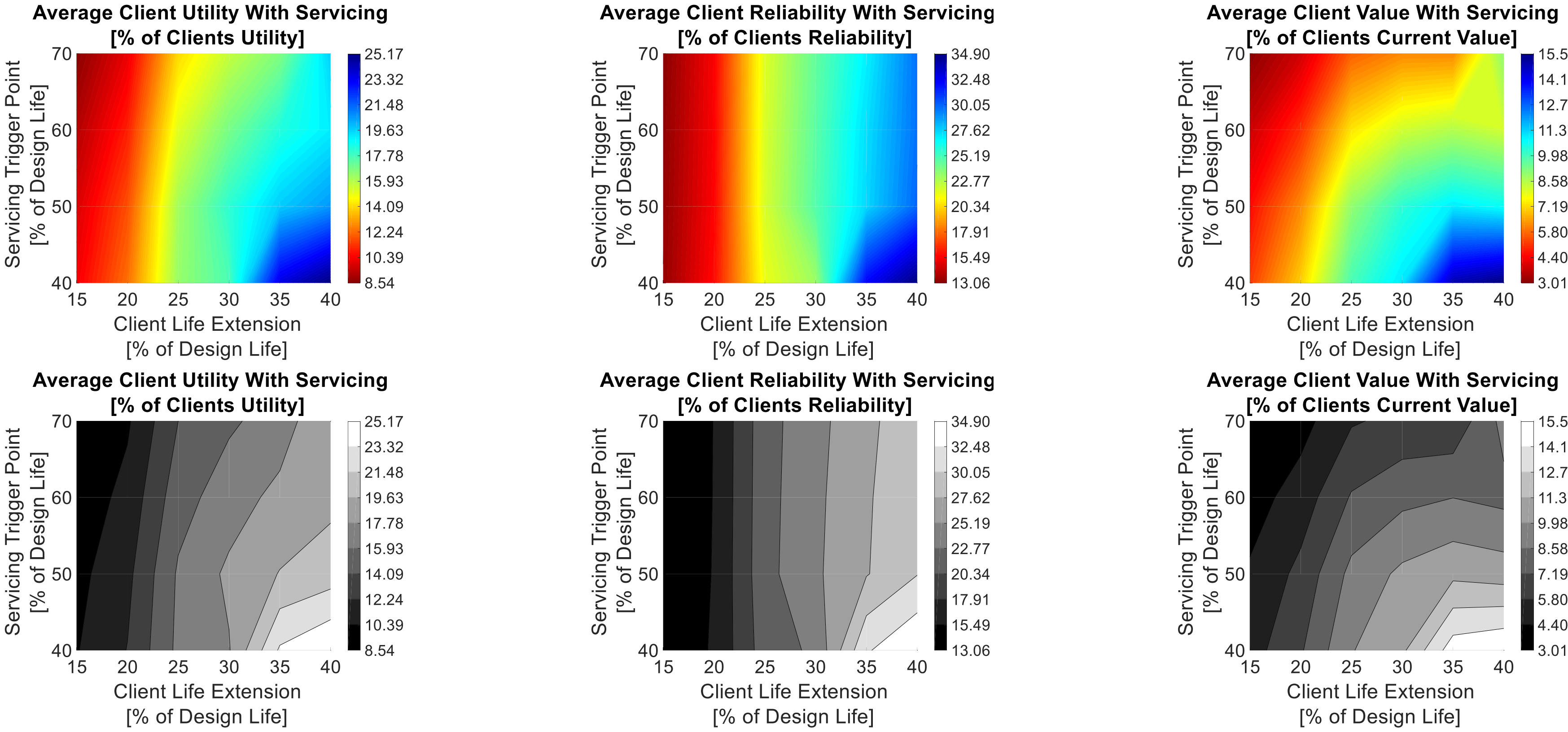


(a) 40% Servicer intended profit (b) 45% Servicer intended profit



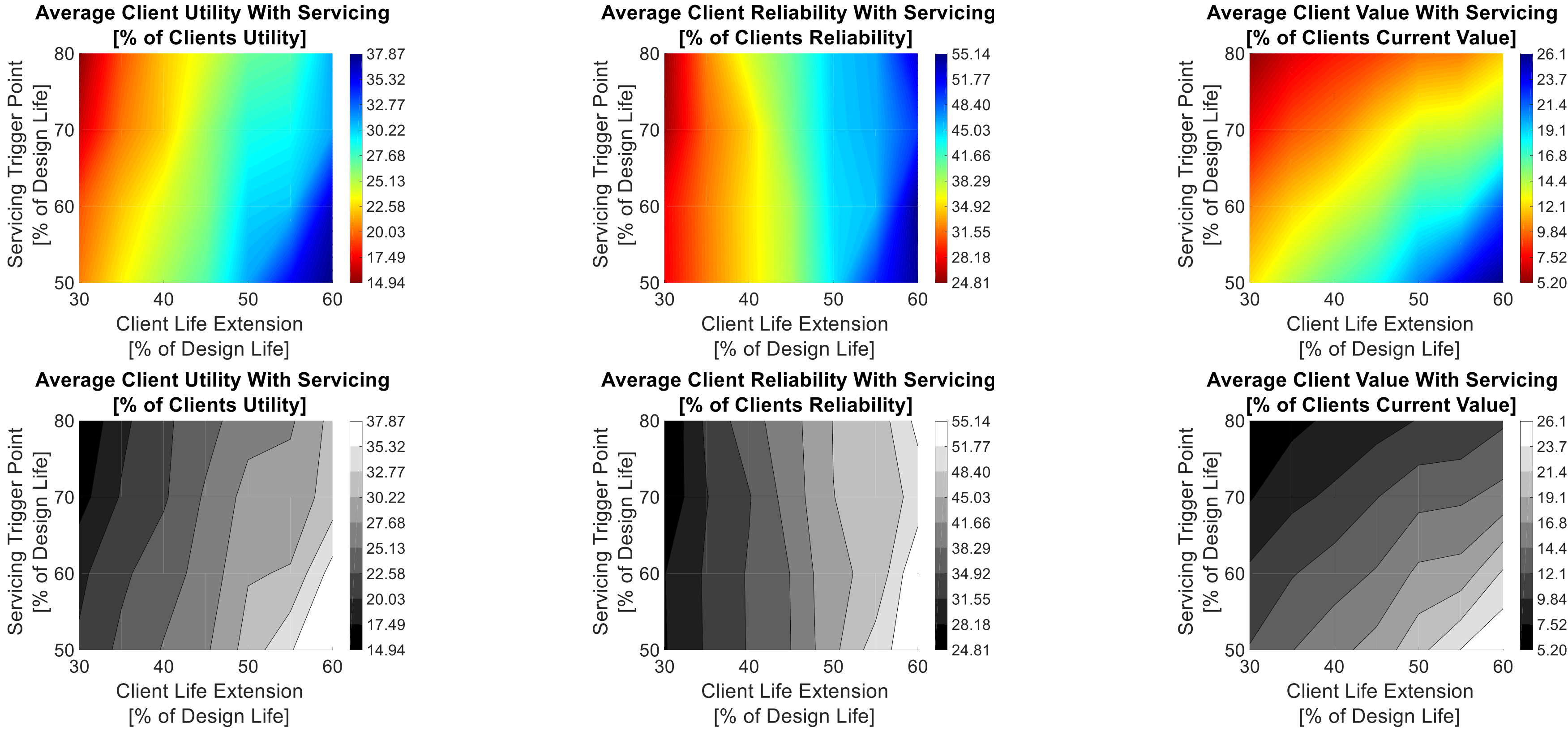
(c) 50% Servicer intended profit (d) 55% Servicer intended profit

Figure I-4 – Solution Exploration Results – Maintenance and Repair – Average Servicer Profit



(a) (b) (c)

Figure I-5 – Solution Exploration Results – Lifetime Extension – Average Client *Utility* (a), Average Client *Reliability* (b), Average Client *Current Value* (c) – (Additional values above that achieved without servicing)



(a) (b) (c)

Figure I-6 – Solution Exploration Results – Maintenance and Repair – – Average Client *Utility* (a), Average Client *Reliability* (b), Average Client *Current Value* (c) – (Additional values above that achieved without servicing)

Appendix J – Use Cases – Servicers Parameters

Table J-1 – Servicers Parameters – Use Cases

Use Case	ID	App.	Type	Life [years]	Estimation Process	Dry Mass [kg]	Prop. Orb. Insert.	Prop. Station Keeping	Weibull Beta	Weibull Theta [years]	Mono-prop. to sell [kg]	Bi-prop. to sell [kg]	Hosted Payl.	Avg. Client Mass Target [kg]	Remarks	Profit @ EOL [%]	ΔV Cap. [km/s]	Total Mass [kg]	Cost [M$]
1 (Pop.1)	1	LE	NONE	20	MF	1000	BP	E	0.3874	8338.4916	0	0	0	1400	GeoStar-3 Based	80	4.875	2038.17	172.12
	2	MR	REFUEL	10	MF	1800	BP	E	0.3874	8338.4916	500	800	0	0	-	40	1.090	5209.53	303.22
1 (Pop.2)	1	LE	NONE	20	MF	1000	BP	E	0.3874	8338.4916	0	0	0	1500	GeoStar-3 Based	100	5.054	2056.86	172.78
	2	MR	REFUEL	10	MF	1800	BP	E	0.3874	8338.4916	500	1000	0	0	-	40	1.090	5545.63	313.61
1 (Pop.3)	1	LE	NONE	20	MF	1000	BP	E	0.3874	8338.4916	0	0	0	1400	GeoStar-3 Based	80	4.875	2038.17	172.12
	2	ME	REFUEL	10	MF	1800	BP	E	0.3874	8338.4916	100	1000	0	0	-	40	1.090	4873.43	292.74
2	1	LE	NONE	20	MF	1000	BP	E	0.3874	8338.4916	0	0	0	1400	GeoStar-3 Based	80	4.875	2038.17	172.12
	2	ME	REFUEL	10	MF	1800	BP	E	0.3874	8338.4916	100	1000	0	0	-	40	1.090	4873.43	292.74
3	1	LE	NONE	20	MF	1000	BP	E	0.3874	8338.4916	0	0	0	1400	GeoStar-3 Based	80	4.875	2038.17	172.12
	2	ME	REFUEL	10	MF	1800	BP	E	0.3874	8338.4916	100	1000	0	0	-	40	1.090	4873.43	292.74
4	1	MR	PAYLOAD AUGM.	10	MF	2000	BP	E	0.3874	8338.4916	0	0	10	0	-	300	1.090	5881.73	800.00