HeRMeS:
Human Repair Missions to GEO Satellites
Services Report

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1 Introduction

1.1 Motivation

Space technologies are the only man-made complex systems worth billions of dollars without maintenance, repair or upgrade infrastructures. The absence of space services has led to spacecrafts designed for the longest operational lifetime possible. Although this strategy minimises the costs, there is a high risk that the spacecraft becomes obsolete before the end of the mission, hindering the deployment of new technologies. This report discusses the economic and technical feasibility of human On-Orbit Servicing (OOS) addressed to GEO (geostationary orbit) satellites in the next decade, advocating the value of added flexibility for space systems.

1.2 History and Definitions

Human servicing has already been proven cost effective in the past [1]:

- *Skylab* was the first US's space station, and included scheduled maintenance activities. However, immediately after launch, the meteoroid shield and one solar panel were torn away by the atmospheric drag. NASA had to train the crew for such unplanned complex repairs, which were performed successfully. In this case, the value of recovering the station outweighed the costs and risks, demonstrating the effectiveness of human improvisation on the field.

- *Solar Maximum Mission (SMM)* was intended to observe solar activity. The failure of its Attitude Control System (ACS), presented a chance for the Space Shuttle to prove its capabilities. After 1 year of training, the SMM was the first uncrewed spacecraft to be serviced and its lifetime was extended from 1 to 5 years. NASA estimated that the cost of servicing was 60 M$, i.e. one-fourth of the replacement costs.

Literature abounds with definitions for on-orbit services (OOS) types [1], [2] that cannot easily be decoupled and categorised; the various service possibilities could be divided into relocation/manipulation, planned/unexpected, maintaining/changing original mission goals, single/multiple service(s) per satellite, amongst others. For simplicity, a concise combination of those is proposed:

- *Assembly*: fitting together of in-space/on-ground manufactured elements into their operational configuration; examples are antennas, photo-voltaic surfaces, large structures that cannot be launched as one finished piece.
- *Salvage*: upkeep of systems according to initial mission; it can be both preventive/planned (e.g. inspection and maintenance) or corrective/unexpected (e.g. repair and deployment in correct orbit).
- *Life extension*: extending/improving the operational life, differently from the initial mission goals; this includes refuelling and upgrade, which are generally planned activities.
- *Disposal*: transferring the satellite into a graveyard orbit at its End Of Life (EOL).

1.3 Methodology and Structure

A creative approach was encouraged for this study supported by a literature review. The assumptions made will be presented in each chapter, progressively defining the constraints for an OOS mission; however, it was important not to combine a rough analysis with a too detailed one, in order to obtain consistent estimates and errors.
This report is structured as follows: firstly, in section 2, a market research is conducted to understand the trends of the GEO satellites industry, adopting the customer's perspective (e.g. a satellite operator); secondly, OOS are discussed from a practical point of view, analysing multiple factors such as tools, Technology Readiness Level (TRL) and servicing techniques for a chosen set of services. A concept of operations follows supported by the analysis of associated off-nominals. Once the high-level requirements and constraints are outlined, a top-down financial analysis is performed. Finally, the long-term benefits of such endeavour are explored to further justify the chosen service system.

2 Geostationary satellites market

2.1 Customer vs Servicer perspectives

The value of servicing is not limited to allow costs savings, but to potential revenue: OOS flexibility provides decision makers with the options (refuel, upgrade, salvage, repair, etc.) that do not need to be set before launch; instead such options depend on the resolution of factors – such as market demand – that were uncertain at the start of the mission. Therefore, the price of servicing becomes a strong mission design variable, accounting for both the customer's and the servicer's points of view. Price is constrained by what a customer is willing to pay (top-threshold), the competitor's price (middle threshold) and the costs for OOS company (bottom-threshold).

2.2 Market trends

The GEO satellites market represents the most rewarding business case due to the high value and accessibility of its assets. The launch frequency trend remains constant in the time-frame shown by Figure 1: a good number of satellites have been launched in the past few years, and these are the ones that are going to be serviced in the next ten years; another peak of launches is forecast for 2030, so the servicer must account for different propulsion technologies (electrical instead of chemical based) and payload capabilities (High-throughput satellites) used. A yearly average demand of 12.5 commercial GEO service missions is forecasted by NSR [3], distributed as in Figure 2. *Life extension* represents the highest demand, with 9 missions per year; *salvage* drives the revenue instead, as OOS providers will be able to charge a premium to recover the asset; *robotics* is intended here as robotic assembly and other manipulations, but has a more-long term potential since satellites are not yet designed to be serviced; finally, *de-orbiting* offers only a limited revenue opportunity. The demand of 12.5 missions is probably going to grow after 2030. Even though this value can be an underestimate of future demand, it is used as a baseline for the analysis; in fact, it represents a safety margin accounting for the dynamic behaviour of the market.

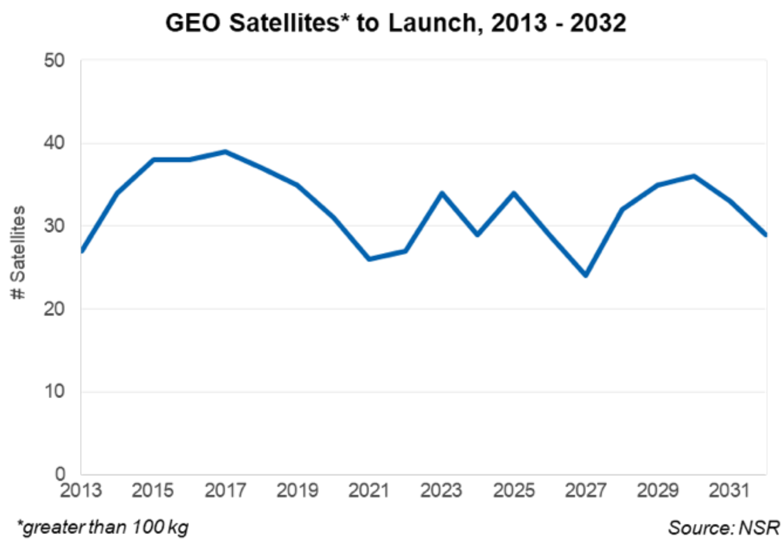


Figure 1: Geo satellites to launch, 2013-2032 [3].

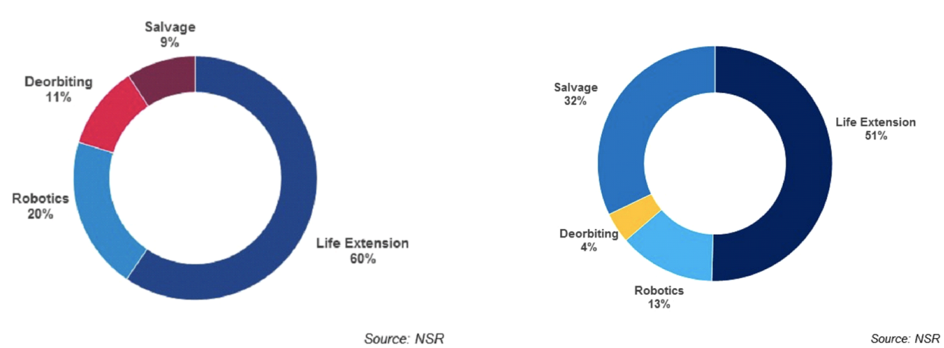


Figure 2: OOS demand (left) and revenue (right) by type of service [3].

2.3 Competitors

By demonstrating robotic OOS, the following companies [3] represent the main competitors to human servicing, especially when it comes to pricing.

Effective Space has been developing a full electric, jet-pack model ($1{\times}1{\times}1.25\ \mathrm{m}^3$, 400 kg) which docks to GEO satellite interface ring, providing attitude and orbit control up to 15 years. A 100 M$ contract for 2 life extension drones has been signed on the 17th of January 2018, with an undisclosed “major regional satellite operator”. The company is also negotiating with suppliers and a launch provider.

Space Logistscs LLC is a subsidiary of Orbital ATK and has studied a similar concept as Effective Space’s one, called MEP. The first scheduled launch was in the late 2018 to service the Intelsat-901 and a second one is planned for the 2020.

3 Mission services

3.1 Services selection

In appendix B, a range of possible *Tasks* for the mission are described. However, there are other significant factors that affect mission design as described bellow. Each of these factors correspond to one column of Figure 3, which displays previously demonstrated operations and seminal missions where the work was performed.

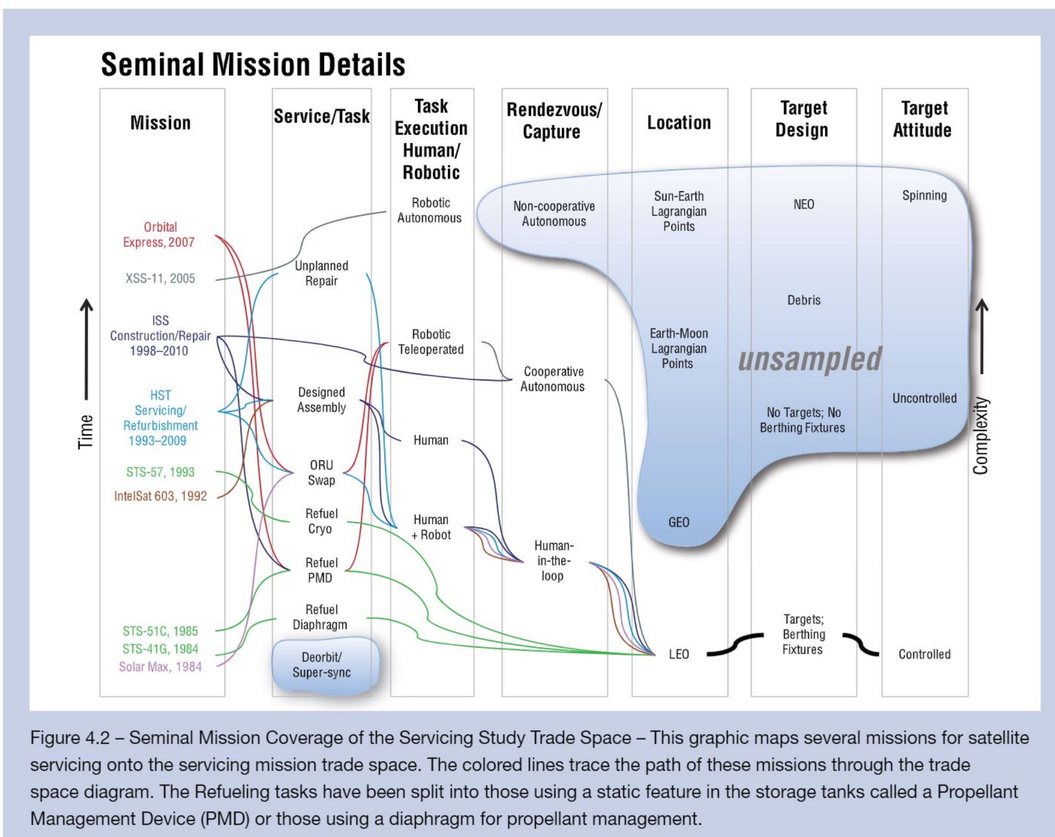


Figure 4.2 – Seminal Mission Coverage of the Servicing Study Trade Space – This graphic maps several missions for satellite servicing onto the servicing mission trade space. The colored lines trace the path of these missions through the trade space diagram. The Refueling tasks have been split into those using a static feature in the storage tanks called a Propellant Management Device (PMD) or those using a diaphragm for propellant management.

Figure 3: Satellite servicing factors [4].

The *Tasks* which involve less complexity are, listing from the least complex, associated with orbit modification, **refuelling** and Orbital Replacement Unit (ORU) exchange.

However, since GEO satellites have not been designed to be serviced, and the majority of the ones currently under development are not planned to be so, these do not feature ORUs contrarily to the Hubble Space Telescope (HST) and International Space Station (ISS), and therefore the range of satellite components that could possibly be replaced is limited. In addition, it should be noted that, although the presence of stations similar to the ISS in GEO would provide numerous opportunities for ORUs as well as designed assembly, concepts such as the European GEOfarm are not sufficiently clear in relation to the role of manned activities as well as maintenance and repair operations. Furthermore, these are only scheduled for the decade of 2030 [5], and human spaceflight projects are frequently delayed.

On the other hand, due to the high levels of radiation of the outer Van Allen belt, the servicing station of this mission will be located 5 000 km above the geostationary belt, which corresponds to a reasonably higher altitude than the graveyard orbit, typically located 300 km above GEO [6]. Consequently, the tug vehicle (to be used for transport of satellites to and from the station) could be used to perform the **super-sync operations** since it would not be logical to tug a satellite, beyond the graveyard orbit, to the station in order to provide it with means to self-super-sync to a lower orbit. Moreover, the tug vehicle could be instrumental to insert satellites in GEO that were not deployed into the GEO belt, for instance, by giving continuation to a prematurely interrupted circularisation of the geostationary transfer orbit.

For these reasons, **refuelling** is the most suitable *task* from a technical point of view to be human-assisted. However, provided their accessibility, **servicing of exterior components** such as solar panels, antennas and the satellite multilayer insulation (MLI) could be an attractive option, even though these are not ORUs per definition. Finally, **unplanned repair/replacement of inner components** of satellites should not be discounted since such *tasks* has never been performed by a robot, thus motivating the human assisted service. However, this would probably involve an unrealistic level of implementation complexity, and the corresponding operations were not detailed. In fact, according to [7] (report from 2015), the average time between the start of assembly to launch of a commercial satellite is 3.3 years, which illustrates the complexity of such operations, and that even servicing exterior components could involve prohibitive complexity, i.e. costs that lead to an unreasonable price tag for the service. In summary, refuelling and service of exterior components are the most realistic operations to conduct, while service of interior components is currently unrealistic.

In terms of *execution*, the “human + robot” element appears at the simple end of the list in light of the shuttle-style grapple arm (Canadarm) being considered a robot; whereas the hundreds of hours of EVA (extravehicular activity) operations on ISS are linked to the category “human”. For this factor, robotic execution, specially when performed autonomously, is considered more complex, thus human operation could represent an advantage. Similarly, *rendezvous and capture* operations are simplified when there is a “human-in-the-loop”, but soon-to-be-launched missions such as NASA’s Restore-L and DARPA’s RSGS (see appendix A) are expected to boost non-cooperative autonomous operations, which will be assigned to the tug vehicle.

On a reflective note, even though not adequate to the context of this project (which should include EVAs), due to the high levels of radiation even 5 000 km above GEO, the instability of the outer Van Allen belt [8], and the costs inherent to human spaceflight, it would probably be desirable to automate most of the servicing tasks (e.g. refuelling). However, human control is still advantageous for certain repairs or workarounds, which might be unique, unpredictable or simply too expensive to automate. The best trade-off for these cases (e.g. solar panel replacement) might be teleoperation, which could be enabled by technologies with increasingly high TRL such as virtual and augmented reality, body tracking devices, head-mounted displays, haptic feedback devices or three-dimensional audio [9].

Regarding *location*, the higher the altitude, the longer the trip duration and latency, with a signal taking at least 0.14 s from Earth to the station, thus increasing complexity.

With respect to *target design*, as discussed in appendix A, the tug vehicle could rely on interfaces such as the Marman clamp ring and bolt holes to grapple the satellites. Nevertheless, these were not designed to be serviced, and do not contain Hubble-esque handrails, making the station mobile servicing system crucial to support the EVAs.

Concerning *target attitude*, in principle, the serviced satellites will be under control of the operators during the operations. In any case, efforts in the field of active debris removal, which could potentially deal with non-operational uncontrolled spinning satellites, suggest that it is possible to stabilise and tug such satellites [10].

Further details on refuelling, solar panels replacement and antenna reflector replacement are discussed in appendix D.

4 Operations schedule

The operation schedule on the station, for all 4 crew members, from arrival can be seen in Figure 4. The crew will work on each satellite for 12 days in total, shifting between different tasks such as exercising, emergency drills, station maintenance, EVA planning, etc. with the first satellite arriving one day after the crew gets to the station denoted in Figure 4 by day 0. The workday on a non EVA day is 8 hours but on an EVA day that has to be extended to 10 hours as seen in Figure 4. The first day of satellite arrival is a non EVA day and will mostly be spent preparing for the first EVA and assessing the condition of the satellite. The major parts of an astronaut's day on ISS today, apart from performing EVAs, are workout, research, education and media events [11]. Research, education and media, while not being stated as tasks that will be handled on the station here, will still probably be a part of everyday tasks for the astronauts on the station and is therefore included in the task of "station maintenance".

4.1 EVA schedule

The major tasks in the EVA have been planned in accordance with the operations mentioned in section 3, the operation schedule and the normal pre-EVA procedures used in human spaceflight today [12]. The EVAs are performed by two astronauts with either one of the two astronauts inside the space station or mission control center conducting the EVA. In Figure 5 the EVA procedure for replacement of solar arrays and refuelling of satellites can be seen. The Schedule starts on the morning of the EVA day after breakfast and morning prep. The camp out procedure is used since it is the most time efficient pre-EVA procedure in the sense that most of the time during the camp out is spent sleeping and that while camping out the astronauts do not have to do anything special, for example exercising.

Hour	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
0600	Sleep	Sleep	BF + MP	Sleep	Sleep	BF + MP	Sleep	Sleep	BF + MP	Sleep	Sleep	BF + MP	Sleep
0700	Sleep	Sleep	EVA Prep	Sleep	Sleep	EVA Prep	Sleep	Sleep	EVA Prep	Sleep	Sleep	EVA Prep	Sleep
0800	BF + MP	BF + MP	EVA Prep	BF + MP	BF + MP	EVA Prep	BF + MP	BF + MP	EVA Prep	BF + MP	BF + MP	EVA Prep	BF + MP
0900	MB	MB	EVA Prep	MB	MB	EVA Prep	MB	MB	EVA Prep	MB	MB	EVA Prep	MB
1000	Ex	Ex	EVA start	Ex	Ex	EVA start	Ex	Ex	EVA start	Ex	Ex	EVA start	Ex
1100	Ex	Ex	EVA	Ex	Ex	EVA	Ex	Ex	EVA	Ex	Ex	EVA	Ex
1200	Ex	Ex	EVA	Ex	Ex	EVA	Ex	Ex	EVA	Ex	Ex	EVA	Ex
1300	Lunch	Lunch	EVA	Lunch	Lunch	EVA	Lunch	Lunch	EVA	Lunch	Lunch	EVA	Lunch
1400	SM	EVA prep	EVA	EMU S	EVA prep	EVA	EMU S	EVA prep	EVA	EMU S	EVA prep	EVA	EMU S
1500	SM	EVA prep	EVA	SM	EVA prep	EVA	SM	EVA prep	EVA	SM	EVA prep	EVA	SM
1600	Leisure	EVA prep	EVA	SM	EVA prep	EVA	ED	EVA prep	EVA	SM	EVA prep	EVA	ED
1700	Leisure	Leisure	EVA	Leisure	Leisure	EVA	Leisure	Leisure	EVA	Leisure	Leisure	EVA	Leisure
1800	Leisure	Leisure	Post EVA	Leisure	Leisure	Post EVA	Leisure	Leisure	Post EVA	Leisure	Leisure	Post EVA	Leisure
1900	Leisure	Leisure(C)	Debriefing	Leisure	Leisure(C)	Debriefing	Leisure	Leisure(C)	Debriefing	Leisure	Leisure(C)	Debriefing	Leisure
2000	Leisure	Leisure(C)	Leisure	Leisure	Leisure(C)	Leisure	Leisure	Leisure(C)	Leisure	Leisure	Leisure(C)	Leisure	Leisure
2100	Leisure	Leisure(C)	Leisure	Leisure	Leisure(C)	Leisure	Leisure	Leisure(C)	Leisure	Leisure	Leisure(C)	Leisure	Leisure
2200	Sleep	Sleep(C)	Sleep	Sleep	Sleep(C)	Sleep	Sleep	Sleep(C)	Sleep	Sleep	Sleep(C)	Sleep	Sleep

Figure 4: Crew operation schedule, with the following abbreviations: BF - Breakfast, MP - Morningprep, MB - Morning Briefing, EX - Exercise, SM - Station Maintenance, C - Camp Out, EMU S - EMU Servicing, ED - Emergency Drill.

Hour	Eva Solar panels	EVA refueling
00	EVA prep	EVA prep
01	100% O2 + DON	100% O2 + DON
02	FINAL Check + DEPRESS	FINAL Check + DEPRESS
03	Make way to SAT	Make way to SAT, CUT TB
04	RM solar panels	Cut lock wire, RM tetriary Cap
05	RM solar panels	RM and stow Safety cap
06	Install adapter	CONN refuelling nozzle, INIT refuel
07	Install solar panels	Refuel
08	Install solar panels	Refuel, DISC refuelling nozzle, WSC
09	WSC,END EVA, REPRESS	End EVA +REPRESS

Figure 5: EVA schedule, with the following abbreviations: ED - Emergency Drill.

4.2 Off-nominal procedure

For the off-nominal case of the EVA decompression sickness was studied in this report. The off-nominal procedure for decompression sickness was divided into four different checklists depending on the severity of the symptoms from the affected astronaut which can be seen in Figure 6 inspired by the off-nominal checklist from the space shuttle mission STS-116 [13]. The checklists are divided into four categories: non-affecting, performance affecting, severe and critical, where critical is an immediate risk of life.

5 Financial analysis

The information from the previous chapters has driven the design of the mission, performed by the other groups. Because the project is still at a conceptual level (Phase A), a top-down cost model – the Advanced Mission Cost Model (AMCM) [14] – was selected; the program wrap and operations costs were also obtained; finally, costs and revenues have been spread over time using tailored distributions, and the break-even point was calculated.

Off Nominal Decompression sickness checklist 1 (mild symptoms such as tingling/numbness):

- Report condition and feeling back to ground crew, wait for medical crew assessment for further actions
- If symptoms does not affect performance keep working.
- Wait for medical crew to report normal state or report off nominal (in case of off nominal proceed to Off nominal Decompression sickness checklist 2.)

Off Nominal Decompression sickness checklist 2 (Moderate symptoms that affects performance):

- If symptoms affects performance immediately start the cleanup procedure (preferably heavier workload on healthy crewmember):
    - Screw back loose screws and attach loose parts or store away
    - Store tools in toolbox
    - Perform workspace cleanup checklist
- Make your way back to the airlock and initiate repress

Off Nominal Decompression sickness checklist 3 (Severe symptoms such as unusual headache tingling/numbness in several places):

- Help affected crew member back to airlock
- Second crew member performs cleanup procedure of workspace:
    - Screw back loose screws and attach loose parts or store away
    - Store tools in toolbox
    - Perform workspace cleanup checklist
- Terminate EVA

Off Nominal Decompression sickness checklist 4 (Serious symptoms such as neurological, lungs or heart):

- ABORT EVA
- Affected astronaut immediately makes its way to the airlock for repress(assisted by unaffected astronaut).

Figure 6: Off nominal checklists for decompression sickness

5.1 Costing

The AMCM provides an estimate for Design, Development, Testing & Evaluation (DDT&E) and production costs for the space station, based on the following formula (see Appendix for constants value):

$$\text{System Cost} = \alpha\, Q^{\beta}\, M^{\Xi}\, \delta^{S}\, \epsilon^{1/(\text{IOC}-1900)}\, B^{\phi}\, \gamma^{D} \tag{1}$$

- *Quantity (Q)* equals one production unit (space station).
- *Dry mass (M)* in pounds is 76 059.
- *Specification (S)* is 2.13 for human habitats.
- *Initial Operating Capability (IOC)* year is 2030.
- *Block number (B)* is 2, assuming some design inheritance from ISS.
- *Difficulty factor (D)* is –2 (low difficulty) since no technological risks or breakthroughs are foreseen.

The block number estimation (pessimistic) and the difficulty factor one (optimistic) compensate each other (the relation is however quite sensitive to D). The formula yields a total DDT&E and production costs of 1 295 M$ (FY 1999), i.e. 2 181 M$ in 2019's currency, using an inflation factor of 1.684 [15].
Additional costs for Phase A and B, operations capability development, launch and landing are

taken into account using wrap factors. For estimating operations costs on a 10 year time frame, the Phase E percentage of total cost for Space Transportation System(STS) and ISS have been considered. A final wrap factor of 10 % is applied to the last subtotal, accounting for program management and systems engineering effort (PM&SE). The final costs breakdown is reported in Table 1 (detailed calculations can be found in the appendix F).

Table 1: Costs breakdown.

Cost component	%	*Cost* [M$ FY 2019]
DDT&E and production	21	2 181
Wrap costs	20	2 155
Operations (10 y)	50	5 299
PM&SE	9	963
TOTAL		10 597

Historical data should be treated carefully, as they assume that spacecraft will cost the same as in the past.

5.2 Pricing & Revenue

As mentioned in the market analysis chapter, price is constrained by various factors: the price that a customer is willing to pay depends on the cost of replacing the satellite with a new one (roughly 200 M$), and on the potential revenue offered by the two options; the Effective Space's contract of 50 M$ per jet-pack module can be used as a reference for the refuelling price. Now that the bottom threshold set by the total costs is known, prices can be adjusted conveniently to the servicer: the added value of flexibility is taken to account for every service type, while the break-even point and yearly positive cashflow should also guarantee a sustainable business model. The price list is reported in Table 2; percentages for services sub-types are derived by service type percentages presented in Figure 2, given the yearly average demand of 12.5.

Table 2: Price list

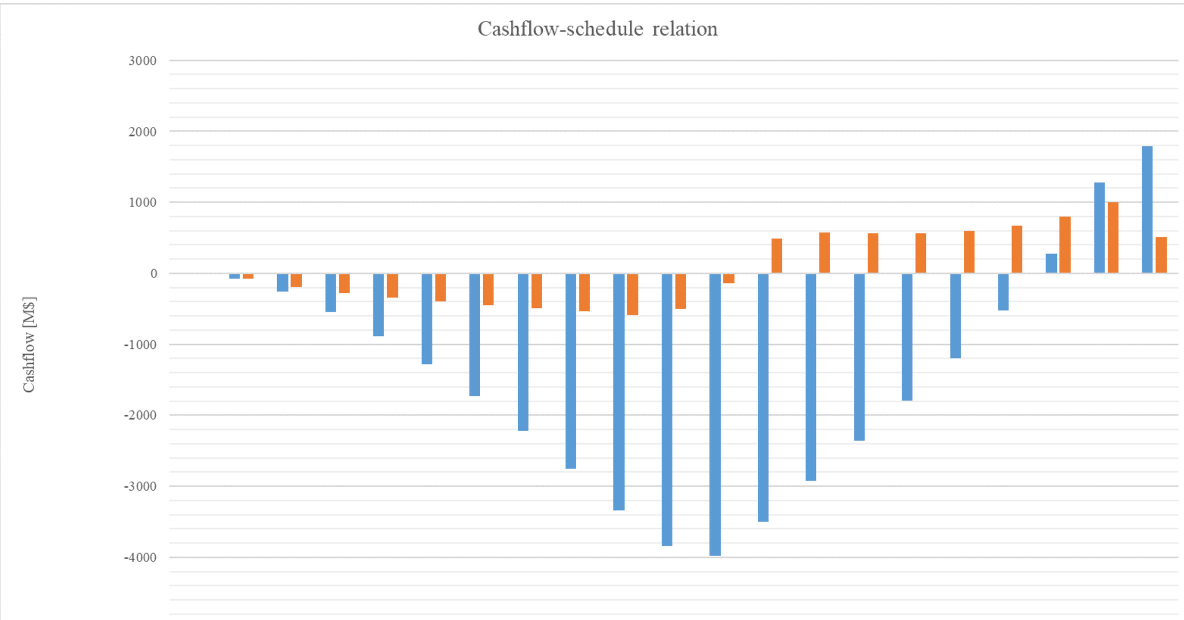
Service type	%	*Service sub-types*	%	*Demand*	*Price/y/demand* [M$]	*Price/y* [M$]
Life extension	60	Refuel	10	1.3	50	63
		Upgrade	10	1.3	150	188
		Refuel+Upgrade	40	5.0	180	900
Salvage	9	Planned	5	0.6	50	31
		Unexpected	4	0.5	150	75
Robotic	20	Relocation	15	1.9	50	94
		Assembly	5		(not considered)	
Disposal	11	Graveyard	8	1.0	10	10
		Recycling	3		(not considered)	
TOTAL				12.5		1 360

5.3 Break-even analysis

The beta curve is used for spreading the costs over the schedule:

$$\text{Cumul. Cost Fraction} = A\,(10F^2 - 20F^3 + 10F^4) + B(10F^3 - 20F^4 + 10F^5) + 5F^4 - 4F^5 \quad (2)$$

A and B parameters have respectively been set to 0.3 and 0, as the costs for this kind of mission are mostly concentrated in the Phase E. Since the first contract might be signed one year in advance of the start of operations, the revenues start from 2029, reaching the expected value within a few years; they will then linearly increase each year, at a slow rate, as the GEO satellite market shows a constant trend; a revenue distribution has been made ad hoc to represent this behaviour. The yearly and cumulative cashflows are finally obtained and have been reported in the plot below (costs and revenues distributions can be found in the appendix F).



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Cumulative Cashflow	0	-72	-262	-540	-885	-1283	-1728	-2218	-2754	-3338	-3838	-3983	-3498	-2922	-2362	-1799	-1201	-528	276	1280	1792
Yearly Cashflow	0	-72	-190	-278	-345	-398	-445	-490	-536	-584	-500	-145	485	577	559	563	598	674	804	1004	512

Figure 7: Cumulative and yearly cashflow showing the break-even point.

The cashflow distribution is consistent with the assumptions and the mission profile: the first couple of years are spent into Phase A and B, registering a small CAPEX (capital expenditure) for the preliminary studies and design definition; the yearly expense increases significantly during the development and testing of the systems (Phase C/D), and reaches the maximum on 2030, when the system is deployed. As we enter the operation stage (Phase E) the yearly cashflow soon becomes positive, providing a good indicator of profitability for the servicing company; the cumulative cashflow also starts increasing, until it reaches the break-even point between 2036–2037, after 18 years from the start of the project and after 8 years from the beginning of operations. On the year 2039 the system is assumed to have reached its EOL, mainly because accurate market predictions where not possible. The servicing company makes an overall profit of 1 792 M$.

6 Long-term services

While improving the serviceability would definitely increase the number of satellites to which service could be provided, and consequently the potential revenue of providing these services, the future remains uncertain, especially in such a budding industry as the one discussed in this project. Moreover, performing any kind of business in space is a very costly venture, not less so when constructing a space station to perform this business, with break-even points far in the future. As such, it is of definite interest to evaluate what kind of other long-term services could potentially be conducted on and with the station, both to justify its construction and ensure the company performing the services' place in the growing space economy.

The first of these potential longer-term services is that of in-orbit manufacturing, which while not necessarily a service in and of itself, is something that could potentially decrease the costs associated with conducting the chosen services for this project. One of the foremost limiting factors in space related businesses is the launch phase, limiting not only the mass and size of objects sent up, but also forcing whatever is to be launched to be able to survive the harsh conditions of launching into space. As such, the prospect of being able to send raw materials could be beneficial. These raw materials would naturally not be sensitive to the harsh conditions of the launch, and their required storage space would also be much more compact than that of finished products. Ideally, these materials would then be used in the manufacture of tools, spare parts or other components on the station relevant to the servicing.

The current state of the art of this kind of manufacturing is unfortunately far from being able to construct anything as complicated as solar panels or other instruments. However, experiments with 3D-printing have been conducted on the ISS, both with more conventional printers [16] as well as a concept called "The Refabricator", capable of recycling plastic waste into printing material [17].

Another branch of in-orbit manufacturing is that of Large Scale Construction. As described briefly in appendix B.8, anything as large and heavy as the ISS would naturally require to be launched in parts to then be assembled in-orbit, something that has obviously already been done. In terms of size however, even more ambitious projects than the ISS have already been proposed by for example JAXA (Japanese Aerospace Exploration Agency), planning on building large solar farms in orbit [18]. In most of these cases though, assembly and/or construction is planned to be autonomous, as in the "SpiderFab" concept by Tethers Unlimited [19]. That being the case though, the station could potentially serve as an overseer hub, providing the production robots with supplies and service, as well as inspection of the built structures or assembly of more advanced parts.

Another somewhat related field showing great potential is that of asteroid mining, in which near-earth asteroids would be mined for resources later to be brought back to earth. These resources would include both regular metallic materials, as well as more precious metals such as platinum. Another resource to be harvested is water, which could not only be used as is in space stations and ships, but also to produce oxygen or rocket fuel [20]. Probes such as JAXA's Hayabusa2 and NASA's OSIRIS-REx have already rendezvoused with asteroids [21], [22], with Hayabusa2 having touched down on its asteroid to collect samples for return to Earth [23]. Furthermore, Planetary Resources is a company already planning on sending probes to evaluate which near-earth asteroids are most promising in terms of resources [24].

Was this business to become successful, new service implications and opportunities would arise. Firstly, any off-world mining of resources requires transportation back to Earth which in turn demands some kind of transport vehicle. Servicing these vehicles by performing refuelling, repairs or upgrades is as such a definite probability. Secondly, the resources transported could be used in the manufacturing and construction discussed earlier.

Finally, scientific experimentation and exploration is a last field in which services could be provided in conjunction with the proposed station. While there certainly are some areas in which the position in GEO does stand out as opposed to LEO, as described in the HERMES – Overall Coordination report, with a noteworthy example being the increased radiation levels, it remains unclear whether the environment is sufficiently different from LEO for a large enough number of experimenters being willing to pay the higher transportation fee to reach our station. Regardless, more opportunities for scientific research in space will always continue to be sought after, as the spots on the ISS are limited in number. As described in the HERMES - Vehicle Design report, the Orion capsule used for bringing astronauts to the station supports some experimentation on-board.

While perhaps the most unlikely among the above cases, potential relocation to the Lunar Orbital Platform-Gateway, planned by NASA for completion in 2026 [25], is a final option for the station. As talks have already begun with private companies to bring supplies and other parts to the Gateway [26], a private company performing maintenance of these transportation vessels or other human transports to and from the surface of the moon or in the further future other planets like Mars is definitely likely [27]. Naturally, this would halt any operations by the station in GEO, but could be considered a sort of back-up scenario in case the GEO-market changes drastically.

7 Conclusions

Naturally, costs of human-rated systems are higher than robotic ones, due to redundancy, fault-tolerance and testing; but the added value of human flexibility outweighs these costs, representing a business opportunity with possible growth of demand in the future: the BEP can be reached within 20 years from the start of the project, ensuring a profit of almost 2 B$. Conducting these services with humans does technically seem possible, with the currently most probable and feasible procedures being refuelling and replacement/upgrades of outer parts such as solar panels and antenna reflectors. Standardisation, in turn, may reduce cost and life of the satellite expected to be serviced. Customers cannot plan for a 45-year lifetime; the servicer, from its perspective, cannot consider all the customer's cases. That's where human flexibility comes into play. Robotics is seen to have a more longer-term application, when automation will have reached a sufficient reliability. However, as long as technical feasibility and low risks are not proven, companies will be reluctant to include servicing into their business plan.

8 Division of work

All authors have performed general paper reviewing and enhancement, including checklist validation and general discussion of ideas and suggestions during meetings. Personal contributions are as follows. **Andrea Mincolla**: Research and writing of sections 1, 2, 5 and 7. **Arthur Grönlund**: Research and writing of section 6 and 7. **Shuta Fukii**: Research of section 3, and appendix D. **Vasco Amaral Grilo**: Research and writing of section 3, and appendices A, B, C, D and E. **Vilhelm Dinevik**: Research and writing of section 4.

References

[1] J. H. Saleh, E. S. Lamassoure, D. E. Hastingd and D. J. Newman, 'Flexibility and value of on-orbit servicing: New customer-centric perspective', vol. 40, no. 2, 2003. DOI: 10.2514/2.3944.

[2] J. Kreisel, 'On-orbit servicing of satellites (oos): Its potential market & impact', 2002.

[3] (), [Online]. Available: https://www.nsr.com/ (visited on).

[4] NASA, 'On-orbit satellite servicing study', NASA, Tech. Rep., 2010. [Online]. Available: https://sspd.gsfc.nasa.gov/images/nasa_satellite%5C%20servicing_project_report_0511.pdf (visited on 30/01/2019).

[5] (2019). European geofarm concept, [Online]. Available: https://www.scribd.com/document/399488309/GEOfarm-Concept (visited on 23/02/2019).

[6] (2018). Graveyard orbit, [Online]. Available: https://en.wikipedia.org/wiki/Graveyard_orbit (visited on 17/02/2019).

[7] L. A. Davis and L. Filip, 'How long does it take to develop and launch government satellite systems?', Aerospace, Tech. Rep., 2015. [Online]. Available: http://www.iceaaonline.com/ready/wp-content/uploads/2014/03/Davis-Satellite-ICEAASoCal-090915.pdf (visited on 23/02/2019).

[8] C. Norberg, Ed., *Human Spaceflight and Exploration*. Springer, 2013.

[9] J. D. Ianni, D. Repperger, R. W. Baker and R. L. Williams, 'Human interfaces for robotic satellite servicing', Air Force Research Laboratory, Tech. Rep., 1999.

[10] M. M. Castronuovo, 'Active space debris removal - a preliminary mission analysis and design', *Acta Astronautica*, vol. 66, no. 10, pp. 648–653, 2010. DOI: 10.1016/j.actaastro.2011.04.017.

[11] (2014). International space station timelines november 12 2014, [Online]. Available: https://www.nasa.gov/sites/default/files/files/111214_tl.pdf (visited on 16/03/2019).

[12] P. e. a. Johnny Conkin, 'Evidence report: Risk of decompression sickness (dcs)', pp. 13–19,

[13] Lyndon B. Johnson Space Center, *EVA Checklist STS-116 Flight Supplement*, 2006.

[14] W. J. Larson and L. K. Pranke, Eds., *Human Spaceflight: Mission Analysis and Design*. McGraw-Hill, 1999.

[15] (2017). Fy17 inflation tables - to be utilized in fy18, [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/2017_nasa_new_start_inflation_index_for_fy18_use_final_dist.xlsx (visited on 14/03/2019).

[16] (2019). 3d printing in zero-g technology demonstration, [Online]. Available: https://www.nasa.gov/mission_pages/station/research/experiments/1115.html (visited on 14/03/2019).

[17] (2019). Refabricator, [Online]. Available: https://www.nasa.gov/mission_pages/station/research/experiments/2356.html (visited on 14/03/2019).

[18] (2019). Research on the space solar power systems, [Online]. Available: http://www.kenkai.jaxa.jp/eng/research/ssps/hmi-index.html (visited on 14/03/2019).

[19] (2019). Spiderfab™ :process for on-orbit construction of kilometer-scale apertures, [Online]. Available: https://www.nasa.gov/sites/default/files/files/Hoyt_2012_PhI_SpiderFab.pdf (visited on 14/03/2019).

[20] (2019). Planetary resources - products, [Online]. Available: https://www.planetaryresources.com/products/ (visited on 14/03/2019).

[21] (2019). Hayabusa2 mission schedule: Provisional version (as of mar. 8, 2019), [Online]. Available: http://www.hayabusa2.jaxa.jp/en/news/schedule/ (visited on 14/03/2019).

[22] (2019). Nasa's newly arrived osiris-rex spacecraft already discovers water on asteroid, [Online]. Available: https://www.nasa.gov/press-release/nasa-s-newly-arrived-osiris-rex-spacecraft-already-discovers-water-on-asteroid (visited on 14/03/2019).

[23] (2019). Image from just after touchdown, [Online]. Available: http://www.hayabusa2.jaxa.jp/en/topics/20190225e_TD1_W1image/ (visited on 14/03/2019).

[24] (2019). Planetary resources - missions, [Online]. Available: https://www.planetaryresources.com/missions/arkyd-301/ (visited on 14/03/2019).

[25] (2019). Lunar outpost, [Online]. Available: https://www.nasa.gov/topics/moon-to-mars/lunar-outpost (visited on 14/03/2019).

[26] (2019). Gateway memorandum for the record, [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/gateway_domestic_and_international_benefits-memo.pdf (visited on 14/03/2019).

[27] (2019). Q&a: Nasa's new spaceship, [Online]. Available: https://www.nasa.gov/feature/questions-nasas-new-spaceship (visited on 14/03/2019).

[28] (2019). Restore-l robotic servicing mission, [Online]. Available: https://sspd.gsfc.nasa.gov/restore-l.html (visited on 14/02/2019).

[29] (2019). Satellite servicing tdm project overview, [Online]. Available: https://www.nasa.gov/mission_pages/tdm/satellite-servicing.html (visited on 14/02/2019).

[30] (2018). Robotic payload for rsgs mission moves to next phase of development, [Online]. Available: https://www.darpa.mil/news-events/2018-08-17 (visited on 14/02/2019).

[31] J. Parrish. (2019). Robotic servicing of geosynchronous satellites (rsgs), [Online]. Available: https://www.darpa.mil/program/robotic-servicing-of-geosynchronous-satellites (visited on 14/02/2019).

[32] (2013). Rrm task : Thermal blanket manipulation, [Online]. Available: https://sspd.gsfc.nasa.gov/rrm_tbmtask.html (visited on 20/02/2019).

[33] (). Launch and deployment: Introduction, [Online]. Available: https://solc.gsfc.nasa.gov/modules/launch/mainMenu_textOnly.php (visited on 09/02/2019).

[34] (2018). List of spacewalks and moonwalks 1965–1999, [Online]. Available: https://en.wikipedia.org/wiki/List_of_spacewalks_and_moonwalks_1965%5C%E2%5C%80%5C%931999 (visited on 09/02/2019).

[35] (2018). Sts-37, [Online]. Available: https://en.wikipedia.org/wiki/STS-37 (visited on 09/02/2019).

[36] (2018). Sts-49, [Online]. Available: https://en.wikipedia.org/wiki/STS-49 (visited on 14/03/2019).

[37] (2019). Solar panels on spacecraft, [Online]. Available: https://en.wikipedia.org/wiki/Solar_panels_on_spacecraft (visited on 09/02/2019).

[38] (2009). Inside a solar cell, ESA, [Online]. Available: https://www.esa.int/Our_Activities/Space_Engineering_Technology/Inside_a_solar_cell (visited on 19/02/2019).

[39] (2018). Sts-61, [Online]. Available: https://en.wikipedia.org/wiki/STS-61 (visited on 09/02/2019).

[40] (2018). List of international space station spacewalks, [Online]. Available: https://en.wikipedia.org/wiki/List_of_International_Space_Station_spacewalks#2018 (visited on 10/02/2019).

[41] (2018). Orbiter boom sensor system, [Online]. Available: https://en.wikipedia.org/wiki/Orbiter_Boom_Sensor_System (visited on 24/02/2019).

[42] (2019). Sts-120, [Online]. Available: https://en.wikipedia.org/wiki/STS-120 (visited on 24/02/2019).

[43] (2017). Refuelling on-orbital satellites, [Online]. Available: https://www.ses.com/blog/refuelling-orbital-satellites (visited on 14/02/2019).

[44] (2019). International flight no. 98, sts-41g, challenger (6), usa, [Online]. Available: http://www.spacefacts.de/mission/english/sts-41g.htm (visited on 14/02/2019).

[45] (2011). Attitude and orbital control systems (aocs), [Online]. Available: http://sci.esa.int/xmm-newton/31314-engineering/?fbodylongid=802 (visited on 09/02/2019).

[46] (2019). Satellite communication - aoc subsystem, [Online]. Available: https://www.tutorialspoint.com/satellite_communication/satellite_communication_aoc_subsystem.htm (visited on 09/02/2019).

[47] (2018). Sts-82, [Online]. Available: https://en.wikipedia.org/wiki/STS-82 (visited on 10/02/2019).

[48] (2018). Sts-103, [Online]. Available: https://en.wikipedia.org/wiki/STS-103 (visited on 10/02/2019).

[49] (2018). Spacecraft thermal control, [Online]. Available: https://en.wikipedia.org/wiki/Spacecraft_thermal_control (visited on 10/02/2019).

[50] (2019). International space station, [Online]. Available: https://en.wikipedia.org/wiki/International_Space_Station (visited on 10/02/2019).

[51] (2019). Heavy-lift launch vehicle, [Online]. Available: https://en.wikipedia.org/wiki/Heavy-lift_launch_vehicle (visited on 10/02/2019).

[52] (2016). Maintenance of the international space station, [Online]. Available: http://www.asc-csa.gc.ca/eng/astronauts/about-the-job/maintenance-of-the-iss.asp (visited on 09/02/2019).

[53] (2018). List of spacewalks and moonwalks 2000–2014, [Online]. Available: https://en.wikipedia.org/wiki/List_of_spacewalks_2000%5C%E2%5C%80%5C%932014 (visited on 09/02/2019).

[54] (2019). Sts-116, [Online]. Available: https://en.wikipedia.org/wiki/STS-116 (visited on 10/02/2019).

[55] (2018). Sts-128, [Online]. Available: https://en.wikipedia.org/wiki/STS-128 (visited on 10/02/2019).

[56] (2019). Batteries in space, [Online]. Available: https://en.wikipedia.org/wiki/Batteries_in_space (visited on 14/02/2019).

[57] (2008). Mission to hubble, [Online]. Available: https://www.nasa.gov/mission_pages/hubble/servicing/SM4/main/Battery_FS_HTML.html (visited on 14/02/2019).

[58] J. C. Liou and N. L. Johnson, 'Risks in space from orbiting debris', vol. 311, no. 5759, pp. 340–341, Jan. 2006. DOI: 10.1126/science.1121337.

[59] ——, 'Instability of the present leo satellite populations', *Advances in Space Research*, vol. 41, no. 7, pp. 1046–1053, Dec. 2008. DOI: 10.1016/j.asr.2007.04.081.

[60] J. C. Liou, N. L. Johnson and N. M. Hill, 'Controlling the growth of future leo debris populations with active debris removal', *Acta Astronautica*, vol. 66, pp. 648–653, 2010. DOI: 10.1016/j.actaastro.2009.08.005.

[61] (2018). Space debris, [Online]. Available: https://www.esa.int/Our_Activities/Operations/Space_Debris/About_space_debris (visited on 14/02/2019).

[62] (2019). Sts-115, [Online]. Available: https://en.wikipedia.org/wiki/STS-115 (visited on 13/02/2019).

[63] (2017). The space drill used by nasa astronauts, [Online]. Available: https://www.popularmechanics.com/space/a24639/space-drill-used-by-nasa-astronauts/ (visited on 13/02/2019).

[64] (2007). Tools of the (astronaut) trade, [Online]. Available: https://www.airspacemag.com/space/tools-of-the-astronaut-trade-15273242/ (visited on 13/02/2019).

[65] (2018). Mobile servicing system, [Online]. Available: https://en.wikipedia.org/wiki/Mobile_Servicing_System (visited on 13/02/2019).

[66] (2018). Dextre, [Online]. Available: https://en.wikipedia.org/wiki/Dextre (visited on 13/02/2019).

[67] (2017). Outgassing, [Online]. Available: https://en.wikipedia.org/wiki/Outgassing (visited on 13/02/2019).

[68] (2017). Tools used by astronauts, [Online]. Available: https://sciencing.com/tools-used-astronauts-6133306.html (visited on 13/02/2019).

[69] R. Garner. (2008). Mission to hubble, [Online]. Available: https://www.nasa.gov/mission_pages/hubble/servicing/series/cats.html (visited on 16/02/2019).

[70] (2019). Extravehicular mobility unit, [Online]. Available: https://en.wikipedia.org/wiki/Extravehicular_Mobility_Unit (visited on 09/03/2019).

[71] (2013). What sort of engine and fuel does a satellite use?, [Online]. Available: https://www.quora.com/What-sort-of-engine-and-fuel-does-a-satellite-use (visited on 19/02/2019).

[72] (2016). Neosat, [Online]. Available: http://www.aerospacengineering.net/?p=9680 (visited on 21/02/2019).

[73] (2018). A job and a half for first eurostar neo mission, [Online]. Available: https://m.esa.int/Our_Activities/Telecommunications_Integrated_Applications/A_job_and_a_half_for_first_Eurostar_Neo_mission (visited on 21/02/2019).

[74] (2018). Boeing 702, [Online]. Available: https://en.wikipedia.org/wiki/Boeing_702 (visited on 23/02/2019).

[75] (2018). Boeing 702, [Online]. Available: https://www.sciencealert.com/the-world-s-first-all-electric-propulsion-satellite-is-now-operational (visited on 23/02/2019).

[76] (). Rrm task : Launch lock removal and vision, [Online]. Available: https://sspd.gsfc.nasa.gov/rrm_llr-vt.html (visited on 17/02/2019).

[77] (). Robotic refueling mission tools, [Online]. Available: https://sspd.gsfc.nasa.gov/rrm_tools.html (visited on 17/02/2019).

[78] (2018). Extravehicular activities (evas) for iss construction, [Online]. Available: http://iss.jaxa.jp/iss/assemble/doc04_e.html (visited on 18/02/2019).

[79] (2010). Sts-130/20a - astronauts remove cupola thermal blankets, Youtube, [Online]. Available: https://www.youtube.com/watch?v=omDFpYFPDeQ (visited on 18/02/2019).

[80] (). Rrm task : Refueling, [Online]. Available: https://sspd.gsfc.nasa.gov/rrm_refueling_task.html (visited on 18/02/2019).

[81] (2019). Space logistics services, [Online]. Available: http://www.northropgrumman.com/Capabilities/SpaceLogistics/Pages/default.aspx (visited on 27/02/2019).

[82] (2018). What is the mission extension vehicle?, [Online]. Available: https://blog.spexcast.com/what-is-the-mission-extension-vehicle/ (visited on 18/02/2019).

[83] W. E. Wiesel, *Spaceflight Dynamics*, 3rd edition, 10. Aphelion Press, 2010, vol. 66.

[84] A. E. Turner, 'Development of geosynchronous satellite servicing', Space Systems/Loral, Tech. Rep., 2010. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.196.7006&rep=rep1&type=pdf (visited on 19/02/2019).

[85] (2015). Average commercial communications satellite launch mass declines, again?, [Online]. Available: https://dsm.forecastinternational.com/wordpress/2015/07/13/average-commercial-communications-satellite-launch-mass-declines-again/ (visited on 19/02/2019).

[86] (2019). N2o4/hydrazine, [Online]. Available: http://www.astronautix.com/n/n2o4hydrazine.html (visited on 19/02/2019).

[87] P. Hill and C. Peterson, *Mechanics and Thermodynamics of Propulsion*, 2nd edition. Pearson, 2010.

[88] (2018). Monomethylhydrazine, [Online]. Available: https://en.wikipedia.org/wiki/Monomethylhydrazine (visited on 14/03/2019).

[89] (2019). Dinitrogen tetroxide, [Online]. Available: https://en.wikipedia.org/wiki/Dinitrogen_tetroxide (visited on 14/03/2019).

[90] P. E. Liley. (2011). Compressibility factor, [Online]. Available: http://www.thermopedia.com/content/645/ (visited on 23/02/2019).

[91] M. Dayah. (2017), [Online]. Available: https://www.ptable.com/ (visited on 23/02/2019).

[92] (2019). What is the flow rate of gasoline station fuel dispensers in liters per second?, [Online]. Available: https://www.quora.com/What-is-the-flow-rate-of-gasoline-station-fuel-dispensers-in-liters-per-second (visited on 14/03/2019).

[93] (2017). Changing how solar power rolls, [Online]. Available: https://www.nasa.gov/mission_pages/station/research/news/changing-how-solar-power-rolls (visited on 24/02/2019).

[94] 'Solar power technologies for future planetary science missions', NASA, Tech. Rep., 2017.

[95] (2007). Astronauts repair torn solar panel during dangerous spacewalk, [Online]. Available: https://www.foxnews.com/story/astronauts-repair-torn-solar-panel-during-dangerous-spacewalk (visited on 26/02/2019).

[96] A. Bulit, A. Varinois, J.-M. Ruault, M. Gollor, J. Roggen and K. Ruf, 'Database of eps key requirements and technical specifications for current and future missions', ESA, Tech. Rep., 2015. [Online]. Available: http://epic-src.eu/wp-content/uploads/EPIC-D2.2-1.2.pdf (visited on 19/02/2019).

[97] (2012). Advanced solar array systems, [Online]. Available: https://www.nasa.gov/offices/oct/home/feature_sas.html (visited on 24/02/2019).

[98] (2017), [Online]. Available: https://www1.grc.nasa.gov/wp-content/uploads/ROSA.png (visited on 24/02/2019).

[99] (2017), [Online]. Available: http://www.satnews.com/images_upload/1603726407/59a6d96e2b674.png (visited on 24/02/2019).

[100] J. Lymer, M. Hanson, A. Tadros, J. Boccio, B. Hollenstein, K. Emerick, S. Doughtery, B. Doggett, J. T. Dorsey, B. D. King and L. Bowman, 'Commercial application of in-space assembly', 2016.

[101] (2018). Large sectional parabolic antennas - 3.0m, 3.7m, 4.5m diameter, [Online]. Available: https://www.elite-antennas.com/large-sectional-parabolic-antennas (visited on 26/02/2019).

[102] (2018). Parabolic reflector antenna gain, [Online]. Available: https://www.electronics-notes.com/articles/antennas-propagation/parabolic-reflector-antenna/antenna-gain-directivity.php (visited on 24/02/2019).

[103] G. Ahmad and S. Mohsin, 'Modern communication satellite antenna technology', University of Engineering and Technology Lahore, Pakistan, Tech. Rep., 2009.

[104] (2016). In-space robotic manufacturing and assembly (irma), [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/nac_tkortes_irma_nov2016_tagged.pdf (visited on 24/02/2019).

[105] (2019). Side deployable antenna, [Online]. Available: https://satsearch.co/products/hps-gmbh-side-deployable-antenna (visited on 26/02/2019).

[106] (2019). Falcon 9, [Online]. Available: https://en.wikipedia.org/wiki/Falcon_9 (visited on 27/02/2019).

[107] (2012). An open letter to the geo satellite community, [Online]. Available: https://sspd.gsfc.nasa.gov/cooperative_servicing_aids.html (visited on 16/02/2019).

[108] (2017). Fixing satellites in space, [Online]. Available: http://www.astronomy.com/news/2017/12/fixing-satellites-in-space (visited on 29/01/2019).

[109] (2019). Sts-51-i, [Online]. Available: https://en.wikipedia.org/wiki/STS-51-I (visited on 09/02/2019).

[110] (2013). Bbc how to build a satellite, Youtube, [Online]. Available: https://www.youtube.com/watch?v=W-1scVSpwbw&list=LLkrkDiKoCo1FS0Gh4QqP-UQ&index=10&t=0s (visited on 19/02/2019).

[111] (2018). Neosat, [Online]. Available: http://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/Neosat (visited on 21/02/2019).

[112] (2013). Engineers create origami-inspired solar array for space deployment, [Online]. Available: https://newatlas.com/origami-inspired-solar-array-space/30016/ (visited on 24/02/2019).

[113] (), [Online]. Available: https://www.electronics-notes.com/articles/antennas-propagation/satellite/satellite_antenna.php (visited on 25/02/2019).

[114] (2018). Mission extension vehicle (mev), [Online]. Available: http://www.northropgrumman.com/Capabilities/SpaceLogistics/Documents/MEV_Factsheet.pdf (visited on 27/02/2019).

[115] A. Kato, 'Report on in-orbit spacecraft failures and the effects of natural environment on them', *TUGBoat*, pp. 127–131, 2016.

Appendices

A Debunking the myth that "Satellites cannot be serviced unless designed to be serviced"

The basis for this myth stems from the belief that 1) without a priori rendezvous targets/aids and docking fixtures, a servicing vehicle cannot adequately locate and reliably rendezvous and dock with an on-orbit satellite, and 2) without ground-tested cooperative interfaces, astronauts cannot perform any level of servicing on a legacy on-orbit satellite that would be of value. [4]

In relation to the capability (of a tug vehicle) to autonomously perform safe, reliable, and fully autonomous rendezvous, as well as proximity operations with a derelict or non-cooperative space objects, there are various missions, targeting the early 2020s for launch, whose vehicles feature these capabilities. For instance, NASA's (National Aeronautics and Space Administration) Restore-L mission, to be launched in mid 2020 [28], is an ambitious, technology-rich endeavour to launch a robotic spacecraft to refuel a live satellite in LEO (low Earth orbit) [29]. Another example is the DARPA Robotic Servicing of Geosynchronous Satellites (RSGS) program, targeted for 2021 [30], which aims to provide high-resolution inspection, anomaly correction, cooperative relocation (potentially of a human station) and upgrade installation [31].

In terms of capture and docking, most in-space non-cooperative vehicles share a number of similar "features" that can be used as docking interfaces. The DARPA Front-end Robotics Enabling Near-term Demonstration (FREND) project has performed ground demonstrations of autonomously grappling the spacecraft's Marman clamp ring and bolt holes with a robotic arm (which both the station and the tug vehicle would have). Both of these features are used to attach the spacecraft to the launch vehicle, thus being structurally sound capture points [4]. For thermal protection reasons, the Marman clamp ring could be covered, but it has been demonstrated that insulation covers can be robotically removed [32], which means the tug vehicle could access such interfaces.

Finally, in relation to 2), years of experience successfully servicing portions of the Hubble Space Telescope that were not originally designed to be serviced represent an encouraging prospect (although these services were facilitated by the fact that some parts of Hubble were designed to be serviced). In effect, engineering evaluation of existing interfaces enables the development of tailor-made tools as well as appropriate astronaut training to perform the required extra-vehicular activities [4]. For a successful service, information concerning the costumer satellite such as technical drawings will be critical.

B On-orbit operations supported by extra-vehicular activities

Currently, there are no plans for human-assisted satellite servicing, and only fully-autonomous operations are being considered. However, the total duration of on-orbit operations (O^3) performed by astronauts during EVAs amount to hundreds of hours. Therefore it is appropriate to identify possible services to GEO satellites from historical examples. This is the focus of the following subsections.

B.1 Satellite deployment

B.1.1 Motivation

Numerous events could prevent a successful deployment, thus jeopardising the entire mission. As examples of mechanical problems, the payload fairings could be inappropriately jettisoned, and the deployment of the antenna system or the solar panels could potentially fail [33]. Propulsion system issues that lead to an incorrect insertion into orbit might also occur.

B.1.2 Historical examples

Table 3: Solar panel deployment [34].

Mission	Astronauts	Start day	EVA duration
Skylab 2 – EVA 2	Pete Conrad and Joseph Kerwin	7/6/1973	3 h 25 min

The astronauts used long-handled cable cutters to remove debris that prevented the remaining solar array wing from deploying (the other was sheared off from the station during its launch), and then forced it to deploy, providing Skylab with the electrical power needed to operate. [34]

Table 4: Antenna deployment [34].

Mission	Astronauts	Start day	EVA duration
STS-37 – EVA 1	Jerry L. Ross and Jerome Apt	7/4/1991	4 h 26 min

The high gain antenna of the Compton Gamma Ray Observatory (CGRO), primary payload of this Space Shuttle Atlantis mission, failed to deploy on command. However, it was freed and manually deployed by Ross and Apt during an unscheduled contingency EVA. [35]

Table 5: Installation of a perigee kick motor [34].

Mission	Astronauts	Start day	EVA duration
STS-49 — EVA 3	Pierre Thuot, Richard Hieb and Thomas Akers	14/5/1992	8 h 29 min

An Assembly of Station by EVA Methods (ASEM) structure was erected in the Shuttle cargo bay by the crew to serve as a platform to aid the astronauts in the hand capture of Intelsat VI. After the trio had pulled the satellite into the payload bay, a new perigee kick motor was added, so that the satellite could be inserted into the intended geosynchronous orbit. This EVA is the only three-person spacewalk in history, and the three spacewalkers also set a new record for elapsed spacewalk time. [36]

B.2 Hardware repair/replacement – solar panels

B.2.1 Motivation

Spacecraft operating in the inner Solar System usually rely on photovoltaic solar panels as power source in order to run the satellite sensors, provide active heating or cooling and enable telemetry. Moreover, solar panels are, for the majority of the satellites, the backbone of the propulsion system [37] (nuclear power could also perform the role of power source). The efficiency of solar panels decreases due to micrometeoroids and space debris collisions as well as radiation [8], even though current solar cells on geostationary satellites still retain 88 % of their original performance after 15 years [38].

B.2.2 Historical example

Table 6: Solar panels replacement [34].

Mission	Astronauts	Start day	EVA duration
STS-61 — EVA 2	Kathryn C. Thornton and Thomas Akers	6/12/1993	6 h 36 min

Thorton rode the remote manipulator system (RMS), also known as Canadarm, to handle the solar arrays while Akers made the cable connections as the team replaced two solar arrays on the HST [34]. The panels were scheduled to be replaced because the temperature variations made them wobble 16 times a day (as the telescope heated up and cooled off while passing from the nighttime side of the Earth to the daytime side and vice versa), thus disturbing Hubble's ability to maintain precise pointing [39].

Table 7: Solar array repair [40].

Mission	Astronauts	Start day	EVA duration
STS-120 — EVA 4	Scott E. Parazynski and Douglas H. Wheelock	3/11/2007	7 h 19 min

In one of the most spectacular EVAs ever performed on the ISS, the Space Shuttle Orbiter Boom Sensor System (OBSS – introduced in the sequence of the Columbia disaster to inspect the Shuttle Thermal Protection System) was used as an extension boom for Canadarm2 [41]. During the EVA, Parazynski was attached to the adjustable portable foot restraint (APFR), which in turn was connected to the boom. Working slowly with direction from Wheelock and the ground team, Parazynski secured five cufflinks to the P6 array using tools such as needlenose pliers [42].

B.3 refuelling

B.3.1 Motivation

Many satellites are healthy, in good operating conditions, and are able to operate beyond their typical 15 years design life [43]. Adding fuel to a satellite can extend its useful life by providing additional station-keeping, manoeuvring, or deorbit propulsion capability [4]. Thus every sector of satellite utilisation (commercial, scientific and security) could use satellite servicing for increased efficiency, providing the benefits of space operations at a lower overall cost.

B.3.2 Preliminary demonstration

Table 8: refuelling [34].

Mission	Astronauts	Start day	EVA duration
STS-41-G — EVA 1	David Leestma and Kathryn D. Sullivan	12/11/1984	3 h 29 min

Leestma and Sullivan (first American woman to perform an EVA) demonstrated the use of the Orbital refuelling System (ORS). This experiment, which involved the transfer of hydrazine (very toxic and corrosive propellant) to a simulated satellite panel (instead of an actual satellite tank), was a demonstration of Shuttle-human-tended capabilities to refuel already orbiting satellites once their self-contained thruster systems have depleted fuel reserves. [44]

B.4 Hardware repair/replacement – scientific instruments

B.4.1 Motivation

Compared to the 5- or 10-year technology "lag" commonly experienced by major scientific and technological development missions, a 2- to 3-year interval to launch a new technology could significantly improve the return from a mission. This is particularly beneficial for technologies that are rapidly developing such as imaging sensors. [4]

B.4.2 Historical example

Table 9: Scientific instrument replacement [34].

Mission	Astronauts	Start day	EVA duration
STS-61 — EVA 3	Story Musgrave and Jeffrey Hoffman	7/12/1993	6 h 47 min

Musgrave and Hoffman replaced the HST Wide Field Planetary Camera (WF/PC, commonly referred to as "Whiffpick") with the WFPC2. The new camera has a higher rating than the previous model, especially in the ultraviolet range, and includes its own spherical aberration correction system. [39]

B.5 Hardware repair/replacement – AOCS

B.5.1 Motivation

The attitude and orbital control systems (AOCS) are responsible for the orientation of a satellite in space, whether it be for telecommunications, Earth observation or for astronomy missions such as the identification of exoplanets [45]. Moreover, AOCS ensure that the orbital perturbations are counterbalanced, and the satellite does not deviate from the desired orbit [46].

B.5.2 Historical examples

Table 10: AOCS repair and replacement [34].

Mission	Astronauts	Start day	EVA duration
STS-61 — EVA 3	Story Musgrave and Jeffrey Hoffman	7/12/1993	6 h 47 min
STS-82 — EVA 3	Mark C. Lee and Steven Smith	16/2/1997	7 h 11 min

Hoffman replaced two magnetometers (the satellite's "compass") of the HST, thus enabling HST to determine its orientation with respect to the Earth's magnetic field. Both original units were suffering from background noise issues. [39]

On another mission to the HST, Lee and Smith replaced one of the four Reaction Wheel Assembly units that use spin momentum to move the telescope towards a target, and maintain it in a stable position [47].

B.6 Hardware repair/replacement – computer

B.6.1 Motivation

The satellite computer is the component responsible for processing the acquired data, and is therefore critical for the mission.

B.6.2 Historical examples

Table 11: Computer replacement [34].

Mission	Astronauts	Start day	EVA duration
STS-103 — EVA 2	Michael Foale and Claude Nicollier	23/12/1999	8 h 10 min

Foale and Nicollier replaced the main computer of the HST. The new computer reduced the burden of flight software maintenance, significantly lowered costs, was 20 times faster, and had six times the memory of previous one. They also replaced one of Hubble's three Fine Guidance Sensors for a refurbished one that had been previously removed from Hubble and serviced on Earth. [48]

B.7 Hardware repair/replacement – thermal protection installation

B.7.1 Motivation

Thermal control is essential to guarantee the optimum performance and success of the mission. It ensures, during all mission phases, that the temperature of the spacecraft's components is within an acceptable range, hence preventing damage or sub-optimal performance. [49].

Table 12: Thermal protection installation [34].

Mission	Astronauts	Start day	EVA duration
STS-82 — EVA 5	Mark C. Lee and Steven Smith	18/2/1997	5 h 17 min

B.7.2 Historical example

Lee and Smith attached several thermal insulation blankets to three equipment compartments at the top of the Support Systems Module section of the HST. This contains key data processing, electronics and scientific instrument telemetry packages. [47]

B.8 Large structures assembly

B.8.1 Motivation

Due to launch vehicle size and payload mass restrictions, it is not possible to directly insert large structures into orbit. Consequently, these should feature modularity in order to be assembled in space.

B.8.2 Historical example

Since 1998 there have been 213 EVAs totalling 1 335 h [40] devoted to the assembly and maintenance of the 420 tonnes ISS [50]. Thus, being 20 times heavier than the maximum Ariane 5 payload to LEO (21 tonnes [51]), ISS is a prime example of the necessity and implementation of large structures assembly.

B.9 Large structures maintenance

B.9.1 Motivation

Unlike space shuttles or space capsules, space stations never return to Earth, hence both preventive and corrective on-orbit maintenance have to be performed. Preventive maintenance involves inspection, replacement and cleaning tasks that the astronauts train for prior to their missions. Corrective maintenance requires the astronauts to fix a broken or non-functional piece of equipment, what often involves on-board training, troubleshooting and testing in order to deal with an unforeseen situation. [52]

B.9.2 Historical examples

Table 13: Solar panel retraction – corrective maintenance [53].

Mission	Astronauts	Start day	EVA duration
STS-116 — EVA 4	Robert Curbeam and Christer Fuglesang	18/12/2006	6 h 38 min

As an example of corrective maintenance, Curbeam and Fuglesang embarked on an unscheduled EVA, and managed to fully close the last eleven bays of the P6-port Solar Array Wing [54].

Table 14: Ammonia tank replacement – preventive maintenance [53].

Mission	Astronauts	Start day	EVA duration
STS-128 — EVA 2	Christer Fuglesang and John D. Olivas	3/9/2009	6 h 39 min

Regarding preventive maintenance, Olivas and Fuglesang installed and connected the new Ammonia Tank Assembly (ATA) which, weighing about 820 kg , was the largest mass ever moved by spacewalking astronauts. Two get ahead tasks were also performed, including the installation of protective lens covers on the End B cameras of the Space Station Remote Manipulator System (SSRMS), known as Canadarm2. [55]

B.10 Hardware repair/replacement – batteries

B.10.1 Motivation

Batteries are used on spacecraft as a means of power storage. Primary batteries contain all their usable energy when assembled and can only be discharged, whereas secondary batteries could be re-charged by an energy source, usually solar panels, and deliver power during periods that the space vehicle is out of direct sunlight. [56]

B.10.2 Historical example

Table 15: Batteries replacement [53].

Mission	Astronauts	Start day	EVA duration
STS-125 — EVA 5	John M. Grunsfeld and Andrew J. Feustel	18/5/2009	7 h 2 min

During the twenty third and final spacewalk to service the Hubble, Grunsfeld and Feustel installed the final battery module [53]. The new batteries are physically stronger, feature higher performance than the old "dry sinter" batteries, and have the added safety feature of a battery isolation switch that electrically dead-faces each connector (no electrical power is present at the connectors while the switch is in the "off" position). The latter characteristic creates a safer environment for astronauts installing the battery modules. [57]

B.11 Active debris removal

Recent numerical studies have shown that the debris environment in low Earth orbit (LEO, defined as the region up to 2 000 km altitude) has reached a point where even if all future launches were cancelled, the debris populations would continue to increase [58], [59]. More precisely, the so-called Kessler Syndrome states that the density of objects in LEO is high enough that these collisions between objects could cause a cascade effect where each collision generates space debris that increases the likelihood of further collisions [60].

A separate but related concern exists in the GEO belt, even though spatial densities in GEO and near the orbits of navigation satellite constellations are smaller by two to three orders of magnitude [61]. These satellites, near the end of life, are placed into “graveyard” orbits above the critical GEO altitude (although this is not a sustainable solution in the long run). However, what is called “super-syncing” a satellite can not be performed if it is “dead” (does not respond) or become uncontrollable [4]. In this case, it would be beneficial to have a satellite servicing system to insert the satellite into the desired end-of-life orbit for two reasons. Firstly, the transfer to a graveyard orbit above GEO requires the same amount of fuel as three months of station-keeping [6]; and secondly the removal would enable the maintenance of a clear GEO belt for operational satellites. Furthermore, if the implementation cost of such service was sufficiently low, and an accurate propellant-remaining estimation was not available, operators could maximise their satellite useful lives by emptying the tanks. Thus not having to underestimate the quantity of propellant and super-syncing earlier than needed.

The installation of a perigee kick motor on an orbiting satellite (see appendix B.1.1) has already been executed with an EVA, and supports the possibility of human assisted active debris removal (ADR) missions.

C Extra-vehicular activities equipment and technology

C.1 General equipment and technology

“If anything would have gone wrong with that bolt, the mission would be over”. This reflection made by astronaut Joe Tanner concerns the mission STS-115, and the installation of the ISS truss segments P3 and P4 [62]. For this case, the pistol-grip tool was essential to free the bolt, and attach a new 14 m long section to the truss structure to the ISS. This illustrates how important tools would be for any EVA of a satellite servicing system mission. The following subsections describe some equipment and technologies essential to EVAs (space suit technologies are addressed by the Human Aspects group).

C.1.1 Pistol-Grip Tool

What is the main tool used by astronauts functions very similarly to a regular power drill [63], with the possibility of selecting the extender accordingly to the task. However, it was specially designed for use in space: hardened against vacuum, resistant to extreme temperatures, and easy to use while wearing gloves [64]. In addition, it features an information screen where the selected rotational speed and torque are displayed [64].

C.1.2 Robotic arms

In order to adequately service satellites and perform maintenance of the supporting station, two types of robotic arms should be considered. Firstly, a large robotic arm with wider range designed to move equipment and supplies around the station, capture and release of visiting vehicles, support astronauts working in space via a foot restraint, service instruments and other payloads attached to the station, and provide some external maintenance; the ISS Canadarm2 is an example of such robotic arm [65]. Secondly, a more dexterous robotic arm, such as the ISS Dextre, designed to handle orbital replacement units (ORUs), able to carry spares (stored on the station) to and from worksites (often being attached to Canadarm2), to install some replacements, and perform repairs when failures occur [66]. Since the station does not include a platform such as the Shuttle payload bay, on which structures could be mounted to support the servicing operations, additional robotic arms might be required.

C.1.3 Trace gas analyser

While servicing a satellite, in the event of outgassing (release of a gas that was dissolved, trapped, frozen or absorbed in some material [67]), the trace gas analyser, which essentially is a small high-performance mass spectrometer, is capable of detecting leaking water from the space suit, escaping oxygen, seeping rocket fuel (possibly from a refuelling operation) or other hazardous gases [64].

C.1.4 Safety tethers

While working in a EVA, according to the “tether protocol”, astronauts are either secured on the suit with two hooks (Russia) or with one hook and a tether attached at the waist (United States), which is 7.5 m tether and made of heat-resistant webbing. The hooks and tether in turn attach to handrails built into the station. The main purpose of the tether (and the hooks) is to prevent the astronaut distancing from the station [64]. Nevertheless, some tethers feature self-closing garbage bags for extra bolts, and others act as toolbelts for the astronaut so that no equipment or tools is lost in space [68], what, even with all the precautions, has still occurred.

C.1.5 Tailor-made equipment

Satellites are generally not designed to be serviced, and accessing inner components could be specially challenging. Therefore, in order to deal with their interfaces, specific tools might be needed. For instance, even though the HST was originally designed to be serviceable, the repair of the the Space Telescope Imaging Spectrograph (STIS) science instrument was not in the initial servicing plan, and required the development of a low torque screwdriver to remove circa 100 small screws. In addition, in order to protect the sensitive interior of the telescope, and help the astronauts contain the screws (and loose debris), tool engineers designed the Fastener Capture Plate, a specially crafted device featuring large enough holes for the screwdriver to enter, but sufficiently small to prevent released screws from floating away into space. EVA simulation in neutral buoyancy laboratory plays a key role in the development and refinement process of such new equipment. [69]

Specific equipment for the proposed servicing missions will be described in section 3.

C.2 Mass budget for tools and spacesuits

The NASA’s EMU (Extravehicular Mobility Unit) spacesuit used for EVAs on ISS weights 55 kg without equipment and 145 kg when fully equipped [70], hence the equipment mass is 90 kg . For the present mission, with redundancy in mind, 4 sets of equally massive equipment were considered, totalling 360 kg . On the other hand, for crew missions, assuming that the suits are not single-size (as the EMU, which is modular) and that each astronaut has a different suit, for a crew of 4 astronauts, the total spacesuits mass without equipment would be 220 kg . In reality, it would suffice to consider a certain number of sizes, but this approach is conservative

D Services details

D.1 refuelling

D.1.1 Propellant selection

The vast majority of GEO satellites rely on chemical propulsion (CP), and more precisely on a propellant mixture of the fuel monomethylhydrazine (MMH) and the oxidiser nitrogen tetroxide (N_2O_4) [71]. That being said, electric propulsion (EP) is becoming increasingly popular for station-keeping and orbit insertion, being a key feature, for instance, of NEOSAT, ESA programme to develop and qualify the new GEO satellite product lines Eurostar Neo (Airbus Defence and Space) and Spacebus Neo (Thales Alenia Space) [72], both based on a Hall thruster and using the noble gas xenon (Xe), common electric propulsion propellant due to its high atomic weight and low ionisation potential [72]. The first satellites based on Eurostar Neo and Spacebus Neo are scheduled to be launched this year [72] and in 2021 [73], respectively, but the first all electric propulsion satellite, the ABS-3A powered by the Boing 702SP [74], became operational in 2015 [75]. These dates allow for refuelling operations targeting mainly CP systems at the beginning of the mission, both CP and EP systems at a subsequent stage, and possibly only EP in the long term future.

In what concerns MMH/N_2O_4, since this bipropellant is hypergolic (components spontaneously ignite when into contact with each other), fuel and oxidiser should be carefully isolated.

A bonus of this propellant selection results from the fact that Orion, selected crew vehicle, relies on MMH as fuel, therefore, if necessary, it could also be refuelled.

D.1.2 Tools

The tools used in the first phase of NASA's RRM (robotic refuelling mission), successfully tested on ISS from 2012 to 2013 [76], could be adapted for human operation. Each of the four tools has the volume of a toaster, and an average mass of 7.5 kg [77], amounting to a total of 30 kg . Additional details of the tools are advanced bellow in agreement with [77].

- **Wire cutter and (thermal) blanket manipulation tool (WCT)**. Used to both snip tiny wires and safely move aside delicate thermal blankets. A spade bit on the tool's tip can slice blanket tape. Its parallel jaw grippers are able to grab a satellite's appendages.

- **Multifunction Tool**. Connects with the appropriate adapter to capture and remove the propellant tank cap.

- **Safety Cap Tool (SCT)**. Removes and stows a typical fuel-valve safety cap and its seal. In addition, small adaptors allow it to manipulate screws and remove caps on the RRM module.

- **Nozzle Tool**. Connects to, opens and ultimately closes a satellite fuel valve using an attached hose. It has an anti-cross-threading feature that ensures it cannot damage the satellite fuel valve by screwing the fuel cap on the wrong way. The fuel cap that the tool leaves behind has a "quick disconnect" fitting that allows for a simpler and more efficient refuelling connection in the future, should it be needed.

D.1.3 Task breakdown

The refuelling operations could be divided into the following tasks:

- **Multilayer insulation (MLI) manipulation**. There is vast EVA experience of dealing with MLI covers [78], as the removal of the thermal blankets of the ISS module Cupola [79] suggests. With humans hands dexterity allied to the WCT, this task should not pose an obstacle as motivated in section B.7.

- **Wire cut**. Lock wire is used to make sure that caps stay in place during the random vibrations that occur while the satellites launches to orbit. Astronauts have to cut through this wire with the aid of the WCT, before the removal of the tertiary and safety caps, to gain access to the fuel valve. [80]

- **Caps removal**. The tertiary and safety caps are removed and stowed with the multifunction tool and the SCT, respectively, making the fuel valve accessible. [80]

- **refuelling**. The nozzle tool is threaded onto the fuel valve, and a sequence of remote commands sent from the station to control the propellant transfer. After completion of the fuel transfer, the nozzle tools disconnects, and leaves behind the "quick disconnect" fitting. [80]

Respecting the first task, in case the MLI is damaged during the operation, or if it is not in adequate conditions for another 15 years of operation, as motivated in section B.7, it could be repaired/replaced.

D.1.4 Off-nominal case

In case it is not possible to proceed with the nominal direct refuelling operations, an independent station-keeping unit could be installed on the satellite. One example of such unit is the Mission Extension Pod (MEP) [81], announced in 2018 by Orbital ATK subsidiary SpaceLogistics. In addition to station-keeping, MEP is capable of longitudinal relocation as well as orbit raise to graveyard orbit. The MEP is designed for satellites with functioning attitude control, and uses a xenon propulsion system and solar power to provide highly efficient and long-term station-keeping. This aligns with the general trend in the space industry of switching from traditional hydrazine-based propulsion systems to low thrust but highly efficient electric propulsion systems. [82]

In case the satellite also requires externally provided attitude control, a more complete unit, such as the SpaceLogistics' Mission Extension Vehicle (MEV) [81]. The MEV is compatible with 80 % of all geosynchronous satellites on orbit as of 2018, and the compatibility should increase during the 2020s.

D.1.5 Mass budget

The mass of propellant m_p could be determined applying the Rocket equation (7.9) of [83] considering that the initial mass m_0 of the serviced satellite after refuelling is equal to the sum between the mass of propellant injected into the satellite m_p and its dry mass m_{dry} . This leads to the following expression:

$$m_p = \left(e^{\frac{n\,\Delta v}{v_{\text{eff}}}} - 1 \right) m_{\text{dry}} \; . \tag{3}$$

where $n\,\Delta v$ is the desired delta-v capability for station-keeping, and v_{eff} if the propellant effective exhaust velocity. Further details are given in the following paragraphs.

$n\,\Delta v$ depends on the station-keeping delta-v requirement per year for a GEO satellite, equal to $\Delta v = 50$ m/s [84], and the desired number of years of satellite lifetime extension, considered to be $n = 15$ (see section 2.2).

Provided the typical lifetime of 15 years of GEO satellites, the refuelling missions would target satellites launched after the year of 2015. According to [85], the average 2015 commercial GEO satellite mass after launch was equal to 4 276 kg . Taking into account the tendency to have increasingly small satellite masses, it was assumed that the average satellite mass after launch of a refuelling costumer is 4 000 kg . In addition, it was considered that the dry mass of a satellite is typically equal to half of its mass after launch, which means that $m_{\text{dry}} = 2\,000$ kg .

v_{eff} is given by the product between the standard gravity $g = 9.80665$ m/s^2 and the vacuum specific impulse I_{sp} of the propulsion system. For the MMH/N_2O_4, a specific impulse of 339 s [86] was considered (even though the exact value varies depending on other factors such as the propulsion chamber pressure); and to estimate the mass of fuel and oxidiser, the optimum oxidiser to fuel mass ratio of 1.34 was used [86] (which was supposed to be linked to the previously referenced specific impulse). For the xenon based EP systems, the NEOSAT specific impulse of 1 500 [72] was used (approximate value for which the thrust to power ratio is maximum for Xe according to figure 14.7 of [87]), which should be interpreted as the average specific impulse of the serviced satellites with a xenon based EP system (similarly, the exact specific impulse of each EP system depends on other factors such has the acceleration voltage).

Admitting that the desired additional lifetime for the satellite could be as long as 15 years, (3) implies that the average mass of MMH/N_2O_4 for each additional year of lifetime is 33.7 kg , of which 42.7 % is MMH and 57.3 % is N_2O_4; and the same figure for Xe is 6.97 kg (approximately one fifth of the CP, and hence lower as expected due to the higher I_{sp} of EP systems). For a lifetime extension of 15 years, per satellite, the required propellant mass is 506 kg for MMH/N_2O_4, and 105 kg for Xe. Consequently, since each year will include 7 refuelling operations (see section 2.2), the total masses per year is 3.5 t for MMH/N_2O_4 (1.5 t of MMH and 2.0 t of N_2O_4) and 0.72 t for Xe, assuming that for each year only one type of refuelling operation, CP or EP, is performed.

Another mass component of the refuelling operations results from the tools mass. According to section D.1.2, for the RRM, the total mass for the tools is 30 kg . For redundancy purposes, it would be prudent to have two complete sets of refuelling tools, hence the total mass would be 60 kg . Assuming the storage structure to be as massive as the tools, the required mass for the tools would be 120 kg . Such figure should be a conservative estimate of the real mass required, since human-adapted tools would in principle be lighter, but in any case it represents a negligible fraction of the mass budget for the station.

In relation to the off-nominal case, the MEV mass amounts to 400 kg , and the MEP, featuring a smaller capability, should be lighter. This should be considered an upper bound given the tendency of space industry to produce increasingly light solutions.

D.1.6 Volume budget

MMH and N_2O_4 have a density of 0.840 g/cm^3 [88] and 1.44 g/cm^3 [89], respectively, i.e. specific volumes equal to 1.14 L/kg and 0.694 L/kg . Hence, taking into account the masses of fuel and oxidiser determined in the previous section, per 7 missions (henceforth designated by "per year"), the total volume of MMH/N_2O_4 is 3.0 m^3 , of which 1.7 m^3 is MMH and 1.4 m^3 is N_2O_4.

The volume calculation for Xe is not as simple because, being a gas, its density strongly depends on the station storage tank temperature T and pressure p (and, more rigorously, also on the compressibility factor Z [90]). Using the Ideal Gas Law ($Z = 1$), for standard pressure ($p_{\mathrm{std}} = 1$ bar) and temperature ($T_{\mathrm{std}} = 0$ °C), with the Xenon molecular weight ($M = 131.29$ g/mol [91]), the Xe specific volume would be 173 L/kg , which means a total volume of 127 m^3 would be required per year. This volume is equal to that of a sphere with 3.1 m of radius, which means it could be more practical to store the Xe at higher pressure or lower temperature to minimise the volume. Such considerations are beyond the scope of the Services group, but are important design variables.

For the volume calculated above, and targeting a reference refuelling time of 3 h , the required volumetric flow rate would be 0.27 L/s , which seems attainable (minimum value in United States for car fuel dispensers is 0.6 L/s [92]).

In terms of the refuelling tools, as mentioned in section D.1.2, each one has the volume of a toaster. Therefore, even with the addition of their storage structure, fitting them into the station should not pose an issue.

D.2 Solar panels replacement

D.2.1 Concept

With the goal of developing more compact lightweight flexible panels, NASA's project ROSA (Roll-Out Solar Array) was tested on ISS in 2017 [93]. The concept has a current technology readiness level (TRL) of 7 [94], and reasonably assuming it reaches full maturity (TRL 9) by 2030, the new solar panels could be based on this concept.

D.2.2 Tools

Specialised tools could be required for the removal of the original solar panels, as for the installation of the new arrays.

D.2.3 Task breakdown

The solar panels replacement operations could be divided into the following tasks:

- **Removal of the original solar panels**. Since the station would be orbiting beyond the typical altitude of the graveyard orbit (300 km above GEO), the release of the original panels to the free space would comply with the present rules imposed by the Inter-Agency Space Debris Coordination Committee (IADC) [6].
- **Installation of the new panels**. If the new solar panel is not compatible with the original solar array drive mechanism (SADM), which ensures that the panels are continuously aligned to receive maximum sunlight, a suitable adaptor, both in terms of mechanical interfaces and electronics, would be required.
- **Deployment**. The solar arrays would deploy autonomously, after the EVA activities, as well as the conclusion of the necessary preliminary tests, are completed.

It is important to notice that, provided the solar arrays deploy before reinsertion of the satellite into the GEO belt, the serviced satellites should be smoothly tugged, without sharp accelerations. This might imply the use of electric propulsion in order to avoid the short impulsive manoeuvres inherent to chemical propulsion (even though the tug vehicle has a chemical propulsion system).

D.2.4 Off-nominal case

If the panel deployment sequence is interrupted due to a mechanical issue, an EVA could be scheduled to correct the problem as motivated in appendix B.1. Furthermore, if tears are detected on the arrays, these could either be repaired with cufflinks (load-bearing straps to relieve the pressure from the snagged area, transferring it from the hinge to the cufflink [42]), as motivated in appendix B.2, or replaced by a new array, depending on the severity of the damage.

In any case, dealing with high voltage solar panels would require additional EVA safety measures. For example, during the aforementioned mission STS-120 of appendix B.2, to reduce the risk of Parazynski being electrocuted by the electricity generated by the damaged panel, all of the metal parts on his space suit were covered with insulating tape (in fact, triple-taped) as were all his tools [95]. In addition, Wheelock was responsible for monitoring Parazynski and his tools positions, guiding him to lean back when too close to the swaying array wing [95].

D.2.5 Mass budget

Considering $P = 10$ kW [96] as a reasonable average power for a commercial geostationary satellite, and admitting that the evolution in solar panel technology is such that the current specific power of flexible fold-out and roll-out arrays of $\gamma = 150$ W/kg [94] would decrease, and therefore this figure could be supposed to include the solar panels storage structure, the mass budget for each solar panel replacement would be 66.7 kg . In order to explore the assumption of increasing solar panel specific power, its useful to derive the following expression:

$$\gamma = \frac{P_u}{m} = \frac{\eta\, P}{\rho\, V} = \frac{\eta\, A\, I}{\rho\, A\, t} = \frac{\eta\, I}{\rho\, t}\ , \tag{4}$$

where P_u is the useful power, m is the solar panel mass, V is its volume, A represents its area, t is the thickness and I is the sunlight intensity. Since the sunlight intensity is not controllable, (4) indicates that a decrease in specific power could be achieved by increased efficiency, decreased density or decreased thickness. While increasingly lighter and thinner panels are expected to become available (even though maintaining structural integrity could represent an obstacle), most experts agree that the efficiency limit of the current concept has almost been reached, and efficiencies higher than 30 % are unlikely to be achieved [38]. New concepts include technologies such as nitride-based materials, inverted metamorphic cells and nanotechnology [38].

D.2.6 Volume budget

Some of the largest telecommunication satellites have arrays of 100 m^2 or more [38], which therefore have to be ingeniously packed into rocket fairings during launch and subsequently be deployed in orbit.

Each ROSA is 4.5 m wide and 14 m long [97], which means it is a 4.5 m height cylinder when rolled. Nevertheless, since ROSA outputs 15 to 20 kW [97], more than the average 10 kW [96] required by the average commercial GEO satellite, there is margin to reduce its size (on top of the reduction enabled by the efficiency increase during the 2020s). Moreover, panels could be undersized to satisfy the power requirement of smaller GEO satellites (but oversized, on the other hand, to ensure end-of-life performance), and the need of larger satellites could be satisfied via the exploration of modularity, as illustrated by the Mega-ROSA architecture [97]. Not only would this approach facilitate storage, possibly allowing the storage of undeployed/rolled panels inside the station, it would improve the structural integrity of the arrays and enable standardisation.

Assuming that each ROSA winglet (designation for the previously mentioned undersized panel) is designed for 5 KW, the form factor of the array is kept constant, and taking 20 kW for the original ROSA output power, a power scaling dictates that the new winglet would be 1.1 m wide and 3.5 m long , which means it corresponds to a 1.1 m height cylinder when undeployed.

The ROSA winglet power output of 5 kW was selected so that the average satellite (10 kW) requires two ROSA winglets. Furthermore, attending to the section 6.1.1 of [96], the maximum power of recent satellites ranges from 2 kW to 18 kW . Consequently, the one-winglet-power is equal to 2.5 times the minimum power, and the four-winglets-power is 11 % larger than the maximum power. This numbers suggest that it would be preferable to design tailor-made solar panels for each serviced satellite. In effect, the scale economy savings that would result from having standard sizes would probably not justify the discrepancy between the provided power and required power. Moreover, for the standard size case, adaptors would be required to ensure compatible voltages and currents, thus increasing the EVA complexity and costs.

On the other hand, judging from images of ROSA [98], [99], the size of the panel supportive structure is considerable, and it might not be practical to store the panels inside the station. In this case, these could either be assembled to the costumer satellite immediately after arrival to the station and removal of the old panels, or stored outside of the station in the non-deployed format and conveniently shielded. That being said, it should be feasible to have the solar panels detached from such a large roll out structure, and design a storage structure adequate to the station dimensions.

D.3 Antenna reflector replacement

D.3.1 Concepts

Assembled antennas offer many architectural choices and business transition opportunities. Figure 8 illustrates, for each architecture, the technical transition applications and benefits.

Selected Architecture	Technical Transition Applications and Benefits
Larger reflectors	• Higher throughput data rate for broadband and comm-on-the-move • Increased transmitted data/$ for reduced cost of service • Extensive frequency reuse for more data per allocated spectrum • Narrower beam possible for directed comm • Better beam isolation, roll-off for improved comm security and capacity
Additional reflectors	• Additional, more, diverse coverage per satellite • Additional throughput via more transponders • Wider geographic coverage, more selective spot coverage to match traffic
Exchangeable reflectors	• Replace or reposition reflectors on-orbit to support a variety of coverage patterns for different and reconfigurable missions throughout satellite life • Ability to launch and install new/alternate reflectors over the mission (via a service like SSL's GEO- Payload Orbital Delivery System (PODS)) to expand the mission and performance

Figure 8: Antenna reflector replacement applications and benefits [100].

It should be noticed that the satellite architectures were not planned to be compatible with larger reflectors or additional reflectors. Consequently, depending on the trade-off between the complexity of adapting the satellite architecture (for instance, redirecting the emitted signal) and the benefits of increasing the diameter, the replacement could be advantageous. In addition, it is worth outlining that, if the diameter of the reflector is large to an extent that it could not fit into the launch vehicle, large deployable antennas could be used (this would avoid the assembly of sectional antennas, common on terrestrial applications [101], in space). Additionally, a reflector with higher efficiency (current typical efficiency ranges from 50 to 70 % [102]).

Regarding exchangeable reflectors, a new antenna surface shaping would allow for a different power distribution of the signal across the region to which the satellite provide coverage. In fact, the target regions seldom have regular shapes as figure 2 of [103] demonstrates, and contour (line of constant effective isotropic radiated power or figure of merit) optimisation is crucial. [103]

Besides the three architectures previously described, there is also the possibility of redirecting it to provide coverage of different regions. However, without changing the properties of the reflector, the power distribution would not change across the covered range (even though the covered regions would change), which limits the benefits of such option.

Finally, for large changes in signal distribution, such as the desire to target a new continent, the tug vehicle could be used to reallocate the GEO satellite to a new orbital slot. Most probably, in order to model the new signal distribution in agreement with the new target region, that would be performed after servicing the satellite antenna reflector.

D.3.2 Tools

Antenna reflectors are mechanically attached to the satellite, and an adequate toolbox to deal with a variety of fasteners would be essential.

D.3.3 Task breakdown

The antenna reflector(s) replacement operations could be divided into the following tasks:

- **Assembly of the new antenna reflector**. EVA assembling experience acquired on ISS would prove valuable for this task.
- **Removal of the original antenna reflector**. Reflectors are usually attached to an arm [104], which in turn is linked to the satellite bus. Therefore this task would in principle involve removing the reflector together with the arm, rather than solely the reflector.
- **Install the new antenna reflector**. This task could possibly involve the deployment of the reflector, especially for large antennas. The alignment of the antenna reflector could be assisted by the use of laser technology to ensure high accuracy positioning.

Additionally, samples (it would not be practical to ship a 2 – 3 m complete antenna dish) of the reflectors could be safely brought back to Earth, with the returning crew, for more in depth studies on the effect of space environment on antenna materials.

D.3.4 Mass budget

Current large deployable reflector antennas from HPS (High Performance Space Structures Systems) have a mass which varies from 25 kg (5 m diameter) to 60 kg (12 m diameter) [105]. Therefore, taking into account the tendency to develop increasingly light structures, it was assumed that, even with the possibility of having larger diameter, the mass budget per antenna would not exceed 60 kg .

D.3.5 Volume budget

The size of the undeployed antenna reflectors would be limited by the diameter of the payload fairing of the launch vehicle, 5.2 m [106] for the Falcon 9 rocket used in the resupply missions. It would not be practical to store inside the station large antenna reflectors whose diameters are close to this maximum value. These could be maintained outside of the station, conveniently shielded, until being installed during an EVA.

E Satellite servicing challenges – brief overview

E.1 Technological challenges

The first challenge is to ensure that a servicing vehicle can locate and subsequently rendezvous and dock with or berth to the customer spacecraft. With existing technologies, this could be (and has been) performed through teleoperation, as long as the communication link time delays and latency are manageable. [4]

Secondly, servicing a spacecraft that was not designed to be berthed, captured, or docked with can be accomplished with some additional planning and specialised tool development. For this matter, as suggested during the presentation workshop, accurate information about the satellite interfaces would be critical.

In general, since satellite servicing requires few new technologies, the key challenge lies in integrating the technologies that already exist into an end-to-end mission. [4]

E.2 Making future mission more serviceable

Although it is possible to service satellites that were not designed to be serviced, taking concrete steps to define and place servicing aids on new spacecraft would maximise the benefits offered by the emerging servicing industry. With this in mind, NASA (National Aeronautics and Space Administration) created a list of cooperative servicing aids [107], some of which are presented in Table 16.

Table 16: Cooperative servicing aids for different levels of spacecraft bus modification.

Modification	Exterior additions	Minor modifications	Redesign and design
Rendezvous and proximity operations	Take closeout photos using LIDAR (light detection and ranging) or infrared	Add solar-powered LED (light-emitting diode) beacons	Add RF (radio frequency) crosslink that provides range information
Capture	Take additional closeout photos of Marman ring (and surrounding area) at launch site	Standardise Marman ring (for capture with a gripper tool)	Add standardised docking feature
refuelling	Add external labels that identify location of the FDVs (fill-and-drain valves) and their respective species	Standardise FDV diameter size, shape, and finish	Add onboard high-accuracy flow meter
Repair	Close thermal blankets with Velcro only; do not use tape or stitching	Add external cameras to observe all deployments in case of anomaly	Design deploy mechanisms with external robotic overdrive feature (hex drive)
Component replacement	Add thermal blanket flap over existing ground test ports	Add external connector that provides access to major spacecraft bus systems	Incorporate modular design for unit replacement
Remote survey	Add external visual markings to identify satellite name (ID number)	Add retroreflectors to tips of antennas and solar arrays	

F Financial Analysis

Constants	*Values*
α	5.56E-04
β	0.5941
Ξ	0.6604
δ	80.599
ε	3.81E-55
ϕ	-0.3553
γ	1.569

Figure 9: Constants for AMCM formula.

Wrap costs (for generic human mission)

Factor	*%*	*[M$]*
Phase A	0.3	7
Phase B	3.5	76
Ops capability devel	15	327
Launch & Landing	80	1745
TOT Wrap (W)		2155
TOT DDT&E+P+W		4335

Operations (10y)	
Avg. Phase E costs for STS & ISS	55%
TOT Operations (O)	5299
TOT DDT&E+P+W+O	9634

ProjManag&SysEng	
% of last subtotal	10%
TOT PM&SE (M)	963
TOT DDT&E+P+W+O+M	10597

Figure 10: Subtotal for costs estimation.

Year	*F*	*CumCost%*	*CumCost*	*YearCost*	*Trend%*	*CumRev*	*YearRev*	*CumCashFlow*	*YearCashFlow*
2019	0	0.000	0	0	0	0	0	0	0
2020	0.05	0.007	72	72	0	0	0	-72	-72
2021	0.1	0.025	262	190	0	0	0	-262	-190
2022	0.15	0.051	540	278	0	0	0	-540	-278
2023	0.2	0.084	885	345	0	0	0	-885	-345
2024	0.25	0.121	1283	398	0	0	0	-1283	-398
2025	0.3	0.163	1728	445	0	0	0	-1728	-445
2026	0.35	0.209	2218	490	0	0	0	-2218	-490
2027	0.4	0.260	2754	536	0	0	0	-2754	-536
2028	0.45	0.315	3338	584	0	0	0	-3338	-584
2029	0.5	0.375	3974	636	0.10	136	136	-3838	-500
2030	0.55	0.440	4663	689	0.40	680	544	-3983	-145
2031	0.6	0.510	5402	739	0.90	1904	1224	-3498	485
2032	0.65	0.584	6186	783	1.00	3264	1360	-2922	577
2033	0.7	0.661	7000	814	1.01	4638	1374	-2362	559
2034	0.75	0.738	7824	824	1.02	6025	1387	-1799	563
2035	0.8	0.814	8627	803	1.03	7426	1401	-1201	598
2036	0.85	0.884	9368	741	1.04	8840	1414	-528	674
2037	0.9	0.943	9992	624	1.05	10268	1428	276	804
2038	0.95	0.984	10430	438	1.06	11710	1442	1280	1004
2039	1	1.000	10597	168	0.50	12390	680	1792	512

Figure 11: Cost, Revenue and Profit.