# Management Team - Feasibility study of a servicing mission for GEO satellites

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***Abstract*—This work has the purpose of studying the feasibility of manned servicing missions for Geosynchronous Equatorial Orbit satellites, intended as a business to be performed continuously in time and not as a single, unique mission. The whole work has been spread onto five different groups, taking care respectively of logistics of the mission, vehicle design, on orbit service itself, human aspects and overall management. This last section is the one carried out by our group, therefore a very broad and brief view of the whole project will be provided in this report. Dedicated and more detailed sections about cost analysis, pricing strategies and considerations and a rough estimation of business model will be presented.**

**Finally, some Off-nominal cases have been considered, as a study of robustness of the whole service and some future developments and perspectives are presented, with the aim of highlighting some flexibility and future feasibility of this business.**

***Index Terms*—Satellite servicing, Business plan, Equity, Debts, Income Statement, Financial Statement, Cash Flow, Cost analysis, AMCM, Development cost, First unit production (FUP) cost, Learning effect, Revenue, Upgrading, Refuelling, Assembling**

*Abstrakt*— Detta arbete har till syfte att prestera en genomförbarhetsstudie om bemannade serviceuppdrag för GEO satelliter, avsett som företag att utföra kontinuerligt i tid, inte som en enda, unikt uppdrag. Hela arbetet har spridits i fem olika grupper, var och en tar hand om respektive uppdragslogistik, fordonsdesign, på omloppstjänst, mänskliga aspekter och samordning och förvaltning. Denna sista avsnittet är den som utförts av vår grupp, därför en mycket bred och kort översikt över hela projektet kommer att tillhandahållas i denna rapport. Dedikerad och mer detaljerad avsnitt om kostnadsanalys, prissättning strategier och överväganden och en grov uppskattning av affärsmodell kommer att presenteras.

Till sist har vissa Off-Nominella fall beaktats, som en rbusthetsstudie av hela tjänsten och några framtida utvecklingar och perspektiv presenteras, i syfte att framhäva några flexibiliteter och framtida genomförbarhet för denna verksamhet.

## LIST OF SYMBOLS

| | |
|---|---|
| $C$ | Cost ($K or $M) |
| CF | Complexity factor |
| $M$ | Module Mass (kg) |
| $W$ | Module Mass (pounds) |
| $Q$ | Module quantity to be produced |
| IOC | Initial Operation Capability (year) |
| S | Specification |
| B | Block number |
| D | Difficulty |
| N | Number of units |
| LR | Learning rate (%) |
| ROE | Return on Equity |
| ROI | Return on Interests |
| R | Yearly Revenue |
| a | Age of satellite |
| L | Lifespan remained |
| P | Net Profit at EOL |

## I. INTRODUCTION

THERE are an infinite number of possible orbits around Earth, but there is one that have the very particular and unique characteristic of having a period equal of Earth's rotation period: the Geosynchronous Equatorial Orbit (GEO). Its feature makes it a very precious and limited resource since satellites in this orbit will be motionless, a fixed point in the sky, from a ground observer, making then possible to communicate continuously with the same area. Since the first satellite launch in 1964, telecommunication companies understood the opportunity this orbit was offering.

Nowadays there are circa 550 spacecrafts in GEO [1], including about 330 are communication satellites. On average 20 satellites reach the end of useful fuel, 14 need to perform a relocation, 10 meet some kind of failure and 20 new spacecrafts are delivered in the GEO orbit every year [2]. These numbers, together with the habit to throw away everything that is broken, makes man thinks that there might be a potential business to perform services in this orbit. This study will explore the feasibility of a servicing business for GEO satellites, investigating the possible profit for a company performing the services and for the costumers paying for them. In order to target a large group of spatial objects having similar characteristics and purposes, has been decided to focus on commercial satellites. This document will present an economical point of view while more technical aspects of how perform the services has been left to the other groups of the Red Team.

This servicing business has been thought to be consisting in multiple GEO missions, performed on a basis of five times per year starting in 2030. In each mission different services could be performed by a crew of three astronauts, such as refuelling old satellites, upgrading them or, after few years of service, even assembling spacecrafts directly in space. Three to four services could be done in a single mission which has been estimated to last at most 25 days. Since exact numbers to understand satellites' cost and revenues, are not available, average values have been used, considering large telecommunication satellites belonging to the main companies in the sector such as Intelsat, SES Americom and EUTELSAT [1].

This report presents values and assumptions considered for the business and details on the method to evaluate the business feasibility. Then results will be presented and a cost analysis is made to determine if this venture could ever be doable and profitable. Important numbers and decisions are then summarized and discussed in a final part where a final judgment is given.

## II. Methods

### A. Group collaboration

As with all projects of this scale, workload must be categorised and distributed to sub-groups within the overall team.

The Red Team are no exception, and were divided into sub-groups for various aspects of the project. This meant that although each group could focus on their particular task, facilitation of proper information-sharing quickly showed itself to be an important driver for the project's success. This lead to the creation of the *Overall Systems Budget*, a spreadsheet with key data regarding the mission.

As is discussed in [3], space mission design is an iterative process. This means that parameter values will constantly be changing, particularly during early stages of the project. In order to ensure all team members were constantly updated on these values, the Overall Systems Budget was continuously updated by each group. The final values for key parameters are summarised in section III.

### B. Cost analysis

To estimate the cost of a space business, different costs need to be taken into account. A space program includes development, production and operations costs [3]. Level of confidence or risks estimation are part of the estimation. Cost analysis is based on global parameters as the program size (or weight in kilograms of hardware), technologies available which can be express in term of technology readiness level (TRL) and schedule. This preliminary study aims to give a rough order of magnitude (ROM) of the cost of the servicing program, from development to the end of the missions.

Several methods can be used for cost analysis [4]. One can use bottom-up estimation, by adding the cost of each subsystem in order to obtain the cost of the overall product. If this method is the more accurate, it is not relevant at this stage of the program as costs for each subsystems are unknown. Parametric estimation can also be used: based on existing space programs, cost models can be developed. This method is relevant when key variables are available. Cost Estimating Relation (CER) gives relation between those key variables and costs (statistic based relations). The last method is estimation using analogy with other space missions. The program is compared to existing space missions and costs are deducted from those earlier design [3]. Parametric and analogy cost estimations can be called top-down estimations, by opposition to the bottom-up estimation. For a preliminary study, top-down estimations are made in order to obtain a ROM for cost.

*a) Assumptions:* In this part, 2010 dollar will be used as a reference to estimate the cost for production and fabrication. The first flight is scheduled for 2030. As a result, preliminary phases will be done between 2019 and 2030, including [4]:

- Preliminary analysis, which defined the content of the program, the goals of the mission and possible solutions.
- Definition phase, more detailed analysis of the program, with cost analysis, schedule, first technical decisions. This phase is vital to control costs during the following steps.
- Development and test phase, which featured preparation for the first launch, development and production of the modules.

For cost estimation, the program is going to last 15 years, between 2030 and 2045. Each year, five missions are being performed, one mission every two months and two months are reserved for one additional mission (in case of unexpected event, aborted mission, or delay in the schedule). Three astronauts participate each mission, each astronaut is supposed to participate two missions in total (as the Human Aspect group found the radiation limit is reached after two missions for most male astronauts). As five to six missions per year are planned, 9 astronauts will be trained for each year of service. As astronauts will be trained for two years, the program needs to take into account the training of 18 astronauts continuously, in addition to 9 operational astronauts each year. The training will start in 2029, as the first launch crew is planned for 2031.

*b) Work Breakdown Structure (WBS):* According to Figure 1 and assumptions, each reusable modules will be produced in two copies (space module and back-up module). Between 75 and 90 copies of non-reusable modules need to be produced over the 15 years program lifetime. The launches are provided by independent companies (ArianeGroup for two launches using Ariane 6 A64 from French Guinea, and United Launch Alliance ULA for five to six launches per year using Vulcan Centaur Heavy). Existing launch pads are to be used. Ariane 6 A64 launch costs €90 million [5] or $101.993 million (March, 04 2019 rate, at 0.8825). Assuming 15.4% rate of inflation, this would have cost $88.690 million for year 2010 (FY 2010). In 2019, Vulcan Centaur Heavy launch price is estimated to $115 million (between one third and one quarter of the cost of Delta 4 Heavy [6]) or $100 million FY 2010.

*c) Models for module development and fabrication costs:* To estimate the cost of the modules development and production cost, several top-bottom methods can be used.

**Method 1**: Mean values for development and production costs can be used [3]. Using Table I, module development cost can be calculated with Equation 1, with $M$, the dry mass of the module in kilogram, $c_{\mathrm{Dev}}$, the development cost in $K per kilogram, and CF, a complexity factor, taking into account the development of new technology for the module (see Table II for values). Equation 2 gives the production cost for the first unit, with $c_{\mathrm{FUP}}$ the production cost in $K per kilogram.

$$C_{\mathrm{Dev}} = M \cdot c_{\mathrm{Dev}} \cdot \mathrm{CF} \tag{1}$$

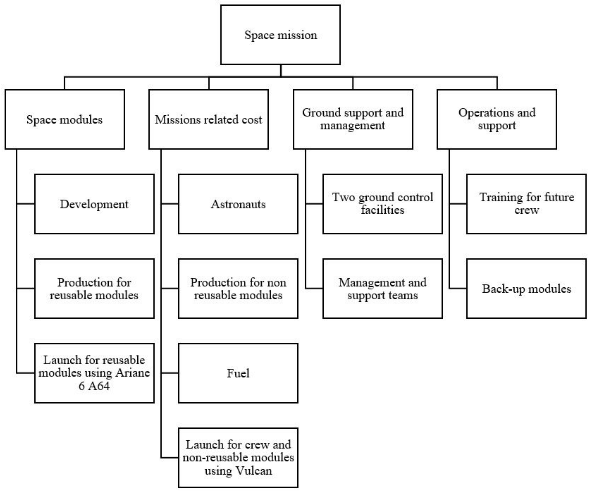


Fig. 1. Program WBS for cost estimation

TABLE I
DEVELOPMENT AND PRODUCTION PRICES FOR MODULES [3]

| | Development cost (FY 2010 $K / kg) | First Unit Production (FY 2010 $K / kg) |
|---|---|---|
| Crewed space vehicle | 698 | 55 |
| Engines | 1500 | 33 |

$$C_{\text{FUP}} = M \cdot c_{\text{FUP}} \tag{2}$$

For each module, complexity factor CF has been determined with the Vehicle Design group, taking into account the development effort to be made.

**Method 2**: A other option for Design, Development, Test, and Evaluation cost analysis is to use the Advanced Missions Cost Model (AMCM) [7]. This model takes into account additional parameters compared to the previous model. It is based on the dry mass of the module (like the previous one), but it also takes into account the number of unit to be produced, the starting year of the program, the type of the mission and estimated difficulty. Equation 3 gives the development and the production cost for $Q$ units, which weigh $M$ (kg), with an Initial Operation Capability (IOC) in 2030. The variable $S$ stands for Specification and depends on the type of mission (see Table XX), the variable $B$ stands for Block Number, and depends of the design inheritance of the module. The variable $D$ evaluates the Difficulty to develop the module. The value is taken in a range between -2.5 for extremely easy to 2.5 for extremely complex design development and production, 0 is the average value. The parameters values can be found in Appendix VII-A. This model gives a cost in $K FY 1999.

$$C_{\text{Dev \& Prod}} = \alpha \cdot Q^{\beta} \cdot M^{\Xi} \cdot \delta^{S} \cdot \epsilon^{\frac{1}{\text{IOC}-1900}} \cdot B^{\Phi} \cdot \gamma^{D} \tag{3}$$

**Method 3**: An third method available for cost calculation is also using CERs. However, by opposition to the AMCM, the model developed by Arney and Wilhite [9] gives two distinct values for development cost and the first unit production cost, using Equation 4, with $k \cdot a$ and $b$, two parameters depending on the mission type, and on the type of cost (development or production) [10]. The values for parameters $k \cdot a$ and $b$ are given in Table IV. In Equation 4, the mass $W$ is given in pounds. This model is in $K FY 2012.

$$C = k \cdot a \cdot W^{b} \tag{4}$$

TABLE II
COMPLEXITY FACTORS [4]

| | Complexity factor |
|---|---|
| Off-the-shelf, minor modifications | 0.2 |
| Basic design exists, few technical issues, 20% new | 0.3 - 0.5 |
| Similar design exists, some technical issues, 89% new | 0.6 - 0.9 |
| Requires new design and qualification; needs some technology development | 1.0 |

TABLE III
SPECIFICATION VALUES [8]

| Specification | S Value |
|---|---|
| Human Reentry | 2.27 |
| Human Habitats | 2.13 |

TABLE IV
ARNEY AND WILHITE MODEL PARAMETERS VALUES [9]

| | Development | | First Unit Production | |
|---|---|---|---|---|
| Mission type | $k \cdot a$ | $b$ | $k \cdot a$ | $b$ |
| Crew Capsule | 285.57 | 0.2667 | 49.923 | 0.2409 |
| In-Space Habitat (4 crew) | 1457.7 | 0.0856 | 46.624 | 0.2146 |
| Propulsive Stage | 29.125 | 0.4554 | 1.8650 | 0.4782 |
| Descent Stage | 168.22 | 0.3152 | 4.8935 | 0.4146 |

**Learning effects**: As some modules are going to be produced several time (up to 90 modules if 6 missions per year for 15 years are accomplished), cost estimation should take into account sensitivity to learning. If AMCM model is already depending of the number of unit to be produced, it's not the case when using methods 1 and 3. Thus, Equation 5 gives the production cost for $N$ units, taking into account the learning rate LR, specified in Table V and $C_{\text{FUP}}$ the cost of the first unit to be produced.

$$C_{\text{Prod}}(N) = C_{\text{FUP}} \cdot N^{B+1} \text{ and } B = \frac{\ln\left(\frac{\text{LR}}{100}\right)}{\ln(2)} \tag{5}$$

### C. Price evaluation

In order to make this business profitable and at the same time, appealing for customers, determining the price for the offered services is a key factor. Since even between commercial GEO satellites there are a lot of differences in terms of dimension, structure and purpose, finding reasonable values to satisfy big and little costumers was challenging. The procedure

TABLE V
LEARNING RATE AS A FUNCTION OF THE NUMBER OF UNITS [4]

| Number of units | LR | $B$ | $B+1$ |
|---|---|---|---|
| Less than 10 units | 95% | -0.074 | 0.926 |
| 10 to 50 units | 90% | -0.152 | 0.848 |
| More than 50 units | 85% | -0.234 | 0.766 |

used to determine the prices was mainly conducted from a costumer point of view to better understand how their profit was changing making use or not of the services. In particular, total costs, revenues and so net benefits were compared at the End Of Life (EOL) of a satellite. Many assumptions has been taken into account, considering average values, and here the most important are summarised:

*a) Refuelling:* Since most of the spacecraft reach their EOL because they simply run out of fuel, it has been assumed that the remaining components are still operating nominally, thus refuelling its tanks will extended its lifespan. Despite tanks that can contain fuel for other 15 years which is the usual lifespan of a commercial spacecraft, the probability that all the other components are still working is unlikely, and so a lower value has been taken: 10 years. After the first refuelling of a satellite, it is then to consider not refillable anymore. Another important aspect which has been considered is that even if the refuelling service is performed before the EOL, the tank can not contain fuel for more than 15 years. So, refuelling a satellite that is 3 years old will not extend its lifetime by 10 years but only by 3, since that is the amount of fuel missing.

*b) Upgrading:* The most important aspect of this service from an economic point of view is that the number of antennas on the satellite will be increased and so the its owner will be able to offer a better service and to a larger network to more subscribers; and so an increased revenue. How this could change is a very non-deterministic variable and depends from many factors such as the area covered from the satellite and type of service offered to its subscriber. After an accurate analysis [11] has been assumed an average increase in the revenue of about 50% doubling the number of antennas.

*c) Technological progress:* As the time goes on, new and more advanced technology is ready for space every year. This leads that a new antenna is better and more performing of an old one. Since the main purpose of the upgrading service is to add new antennas and replace the old ones with their new version, the consequences of this technological advancement has to be considered. Nowadays, the revenue of a communications satellite is very proportional to its bit-rate and has been seen [11] that the bit rate is increasing of a factor 10 every 7 years. This will increase the revenue of the satellite but, at the same time, the owner would probably decrease the prices for his subscriber. Finally, an increase of 5% in revenue every 7 year passed from the actual technology, has been add when a satellite is upgraded. This means an average increase of 0.7% per year of the satellite to add in the moment that the satellite is upgraded.

*d) Assembling:* Since assembling a spacecraft in space is something never done before (with minor exceptions such as the ISS, Hubble); it has been assumed that a minimum of 2 years are necessary before to start to perform this service. This time is needed mainly to get a minimum experience in these missions and also build a reliable service where customers are not afraid in spending a large amount of money. At the same time, a short period has been chosen since the technology to perform this service is ready and will not require anything particularly different from what is already in use. It has been estimated also that a big assembled satellite will be able to cover the same functions performed from two smaller satellites. The cost for a costumer other then the service's price is also the launch, the material to assemble (solar arrays, antennas) and the spacecraft which would probably cost more of a single satellite but less than two new ones.

*e) Cost and revenue:* To estimate the cost to launch a new satellite different examples have been considered and the this value has been average around \$ 300-350 million in total between launch and building the new satellite [12][13]. The revenue is the yearly income for the customer. The starting valued has been decided to be \$ 45 million [14] averaging the profit of different communications companies.

The comparison used a simple model which takes into account only the main aspects to determine the final profit, such as remaining life time, revenue and cost for each different service. Setting before some variables as:

| | |
|---|---|
| $C_i$ | Cost |
| $R_i$ | Yearly revenue |
| $a$ | Age of satellite |
| $L_i$ | Lifespan remained |
| $P_i$ | Net Profit at EOL |

*1) New Satellite:*

$$R_{ns} = R + 0.05 \cdot 11R \tag{6}$$

Since the mission would start 11 years from now

*2) Refuelling:*

$$L_r = L + 10 \tag{7}$$

*3) Upgrading:*

$$R_u = R + 0.5R + 1.5R \cdot 0.05a \tag{8}$$

*4) Refuelling&Upgrading:*

$$L_{r\&u} = L + 10 \tag{9}$$

$$R_{r\&u} = R + 0.5R + 1.5R \cdot 0.05a \tag{10}$$

*5) Assembling:*

$$R_a = 2(R + 0.5R + 1.5R \cdot 0.05 \cdot 14) \tag{11}$$

Since it is reasonable to assume that this service will start 14 years from now

The final profit at EOL is calculated then as:

$$P_i = R_i \cdot L_i - C_i \tag{12}$$

Comparing then the different profits and trying to change the cost of each of them,has been possible to decide and set a price for these services.

### D. Business Model

*a) Introduction:* Apart from the cash flows that can be quite easily evaluated, a deeper economical/business analysis is needed to evaluate the sustainability of the whole project. The strategy used for the rough business plan design will be presented in this section, together with some Economics concepts useful for the understanding of the same.

*b) Key definitions:* First of all, it is worth to mention the two type of analysis[1] involved in this business plan study:

1) Financial Statement (Cash Flow analysis);
2) Income Statement (Equity and Debts analysis).

These two analyses are not equivalent to one another, because they underline and highlight different aspects of the business under study. Particularly, the cash flow analysis is used to keep track of the money movements when they are actually performed (i.e. a payment spread over 10 years is accounted only for what is the money movement in the current year), cash speaking, in order to be sure that, despite all the types of movements coming from loans, debts, interests and all the other peculiarities of the business, the income flows are always[2] under control.

The Equity and Debts analysis has the role of highlighting what is the actual value of the business, also amortizing all the fixed costs to the whole life cycle of the considered product (it is simply the ratio total cost over lifetime) and accounting the money movements at the sign of the contract (i.e. A 10 year spread payment is accounted as its whole value at the year of the contract subscription). One should detach from the concept that debts are bad, because a debt today could likely mean an investment, therefore more money in the future. Coming back to the definitions, it is worth to become confident with the concept of Equity: *Equity = Internally Invested Capital + Assets*. The Equity represents exactly what is the current value of the business. Even if the capital is not cash any longer, one should not forget that those money have been turned into assets and a business, which actually have a value and wouldn't be considered without this kind of analysis.

Finally, the last two definitions presented here have the purpose to evaluate the final value of the business plan:

- ROE (Return on Equity), i.e. what is the return that internal capital and assets are producing;
- ROI (Return on Investment) i.e. what is the return that all the capital invested (also coming from investors) is producing.

*c) Assumptions:* The total initial capital assumed is 13 Billion dollars, with a participation of:

- Small founded Company: 1 Billion dollars;
- Corporate participation: 6 Billion dollars;
- Money from investors: 6 Billion dollars.

This kind of division of the capital has the only purpose of highlighting that differently sized companies could be involved in the Business. Again about the initialization of the analysis, all the initial costs will be considered taking place at year 0. This is not realistic on a practical point of view, to set up such resources many years are required, however this assumption is reliable and consistent when it comes to analyze the business just during the service time.

From the investors point of view, the considered investment has the following properties, useful to compute the payback time and the Net Present Values of the investment itself:

- 20% interests (Typical interest factor when investing in a considered risky business);
- 2% annual inflation rate.

The incomes have been estimated as changing in time. Out of 15 years, in year 1 and year 2 only upgrading and refuelling services are available, with the income per mission estimated as if, on average, 50% of the satellites requested both refuelling and upgrading, 25% refuelling only and 25% upgrading only. Let us call this average mission *Type 1*. From year 3 on, also the assembling service is available, with its own particular income and complexity (average mission, with providing 1 assemble only, called *Type 2*, for reasons that will be clear in a few words). The assumption used for the incomes from year 3 on is then to have an average mission statistically made of 50% *Type 1* cases and 50% *Type 2* cases.

The final assumptions of this model are taxes fixed to 12.5% of the annual income, no annual dividends to exist, costs coming from what presented in the Cost Analysis Method 1 (presented in Sections II-B and III-B). Practically speaking, this would mean that the subjects contributing to the equity of the business wouldn't receive any part of the annual cash flows, with all of them re-invested in the company and contributing to the Equity growth. It would never happen in a real running business, but this simple assumption allows to keep an easy track of the Equity trend and the potential value variation of the activity.

### E. Off-Nominals

*a) Introduction:* Unforeseen situations can always happen and, generally speaking, a system must be robust and stable enough to endure not get severely damaged from them. In this part the method of analysis of Off-Nominal cases will be presented, whereas the actual consequences and the solution strategies will be given in sections III-E and IV-F respectively.

*b) Strategy:* The robustness has been studied considering the effects on the whole service of some of the Off-Nominal cases presented by the other groups (the most critical ones), together with some cases that are more peculiar on their more economical rather than technical consequences.

## III. RESULTS

### A. Overall Systems Budget

Table VI summarises the key values of the Red Team. The data is comprised mainly of the Vehicle, Logistical and Human Aspects groups.

[1] A third point is usually considered, the so called "Balance Sheet", showing the actual physical possessions of the venture. It is not considered here, because it wouldn't highlight the value of the business and it is indeed hard to estimates and categorize assets for such a long time plan.

[2] Note that negative movements don't necessarily mean a bad business, this is why both the analysis are needed

TABLE VI
OVERALL SYSTEMS BUDGET SUMMARISED

| Parameter | Value |
|---|---|
| Total mass | 38.5 t |
| Meeting Orbit Alt. | 25 000 km |
| Chasing Orbit Alt. | 33 000 km |
| Total mission time | 25 d |
| Total $\Delta$V | 3.15 km/s |
| Total power consumption | 1.55 kW |
| Volume required | 20 m$^3$ |

## B. Cost analysis

*a) Modules cost:* As presented in section II-B, this study proposes three methods to estimate the modules cost. In this section, those method's results are presented based on the modules presented in Appendix VII-B.

**Method 1**: With a estimated development cost of 698 $K per kilogram for crewed module and 1500 $K per kilogram for engines (see Table I), and the modules mass presented in Appendix VII-B, development costs for each module are obtained. In the same manner, estimated costs for the first unit (FU) production of each module are given in Figure 8 in Appendix VII-C. The cost are divided in non-recurring cost (initial costs), with development and production of reusable modules like the mission module, and recurring costs (or mission costs) including production for non-reusable modules. As some module are produced in large quantities, learning effects need to be added to the cost estimation. Using Equation 5, the mission cost can be calculated for each mission:

- Cost for each new module is calculated to take into account a learning effect
- The Launch Reentry Vehicle cost will be separated between 10 missions (as it can be used for 10 missions).

The total cost, after 80 missions using this method is $15 874.851 million, the cost distribution is presented in Table VII.

TABLE VII
COST DISTRIBUTION USING DATA FROM [3]

| Cost | Value ($M FY 2010) |
|---|---|
| Development cost (all modules) | 6 836.840 |
| Reserve (40% of development cost) | 2 734.736 |
| Reusable modules production | 1 962.400 |
| Non-reusable modules production (80 missions) | 7 075.611 |
| Total (without reserve) | 15 874.851 |
| Total (with reserve) | 18 609.587 |

**Method 2**: Using the AMCM, all development and production costs for the modules are calculated at once (see Equation 3). As the result is given for year 1999 dollar, it has been actualized in 2010 dollar. The inflation rate between 1999 and 2010 used in the calculation is 2.48%. Using this method, the development and the production cost comes to $34 923.954 million.

**Method 3**: Using the model developed by Arney and Wilhite [9], cost for development and FU production are calculated. Using an inflation rate of 1.61% between 2010 and 2012, the development and production cost comes to $44 248.02 million. Detailled costs are presented in Table VIII.

TABLE VIII
COST DISTRIBUTION USING ARNEY & WILHITE MODEL

| Cost | Value ($M FY 2010) |
|---|---|
| Development cost (all modules) | 20 529.29 |
| Reserve (40% of development cost) | 8 211.71 |
| Reusable modules production | 1 793.53 |
| Non-reusable modules production (80 missions) | 21 825.20 |
| Total (without reserve) | 44 248.02 |
| Total (with reserve) | 52 459.74 |

*b) Initial costs:* Initial costs are including costs of the development and the production of the reusable modules and their back-up modules, the reserve and the cost to launch the modules into space. If we are using Method 1 for the module cost estimation, all those costs are already presented in Table VII, and only two launches using Ariane 6 A64 need to be added, $C_{\text{Launch}} = \$88.690M$. Thus, using Equation 13, set-up will cost $11 707.591 million (FY 2010), developement and production costs are calculated using Method 1.

$$C_{\text{Initial}} = 2 \cdot C_{\text{Launch}} + C_{\text{Dev}} + C_{\text{Prod}} + C_{\text{Reserve}} \tag{13}$$

*c) Mission costs estimation:* To estimate the cost of each mission, several redundant costs are included (FY 2010):

- Non-reusable modules production cost, this cost is calculated for each mission, taking into account a learning effect $C_{\text{Module}}(N)$, with $N$ the mission number.
- Fuel cost, this cost is estimated once for all missions. Assuming all modules are completely refuelled before each mission and reasonable price for fuels, the fuel cost is $C_{\text{Fuel}} = \$155.5K$.
- Astronaut cost, also estimated once for all missions. It is assumed the global cost per astronaut and per day in space is of $\$1M$ (to be compared with $\$7.5M$ on the international space station (ISS), and $\$5.5M$ on Skylab [15]). The program is a commercial program, the servicing mission is starting in 2030 and by then, it is assumed the cost will be lower. Thus, for 3 astronauts and 25 days in space, $C_{\text{Astronaut}} = \$75M$.
- Launch cost, using Vulcan ACES, estimated once for all missions, $C_{\text{Launch}} = \$100M$.

Thus, the global cost of one mission is given by Equation 14, with N the mission number. The mission costs are presented in the Figure 2, $C_{\text{Module}}(N)$ is calculated using method 1 (FY 2010).

$$C_{\text{Mission}}(N) = C_{\text{Launch}} + C_{\text{Module}}(N) + C_{\text{Astronaut}} + C_{\text{Fuel}} \tag{14}$$

*d) Annual cost estimation:* Every year, 5 missions are planned, training for 18 new astronauts is taking into account (with $80 K per trainee and per instructor (3 instructors)) and two ground facilities are budgeted ($ 600 M per year for both facilities). For year 1, the cost are presented in Table IX (mission cost is calculated using method 1).

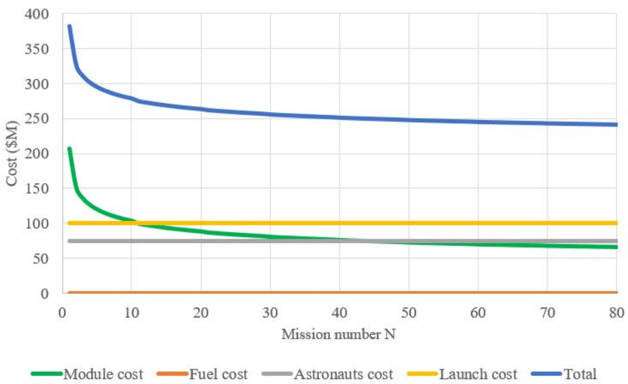


Fig. 2. Mission cost evolution over the program lifetime (80 missions)

TABLE IX
ANNUAL COST (YEAR 1)

| Cost | Value ($M FY 2010) |
|---|---|
| 5 missions | 1 613.51 |
| Ground facilities | 600 |
| Training | 1.68 |
| Total | 2 215.19 |

### C. Price Evaluation

With the aim to make the services offered appealing for customers, it has been decided to set their cost in such a was as to make them more profitable than launching a new satellite. There are two different main category of services and they have been analyzed differently: Refuelling& Upgrading and Assembling.

1) Refuelling&Upgrading
Using values presented in II-C has been calculated that the average total profit for a new satellite is almost $ 400 million at its EOL. Different set of prices have been considered for different cases among which the most relevant are:
   - Refuelling a satellite at its EOL;
   - Upgrading a satellite which is 6 years old;
   - Upgrading a satellite which is new;
   - Refuelling&Upgrading a satellite at its EOL;
   - Refuelling&Upgrading a satellite which is 7 years old;

   After careful evaluation of the business model, it has been decided to set the prices for those services as following:
   - Refuelling $ 25 Millions
   - Upgrading $150 Millions
   - Refuelling&Upgrading $175 Millions

   With these prices, all of the services will be more profitable than $ 400 million for the costumers and so more convenient compare to launch a new satellite. These results are presented in Figure 3
   As can be seen from the graph, some of these services, in particular if performed at the beginning of the satellite's lifespan could give a net profit until 3 times higher than launching a new satellite.

2) Assembling
In this scenario the comparison is different since, as said in section II-C, a newly-assembled satellite is going to handle the functions of two satellites. It follows that the profit comparison has to be done with the one of two new satellites. In addition to this, another case that has been analysed is the upgrading of those two new satellites right after their launch in order to show how assembling is still the best option. The price for the assembling service has been set at $ 400 million, considered that the cost of the launch of the components of the satellite is still in costumers' hands. The total final profit at EOL will be almost the double of launching new satellites and greater, with a little margin, than upgrading them as shown in Figure 4.

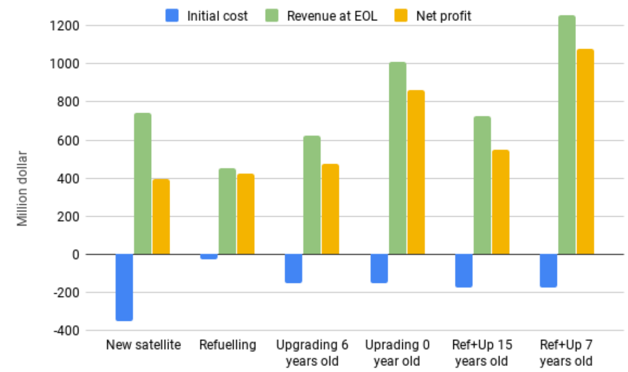


Fig. 3. Profit comparison between most relevant options

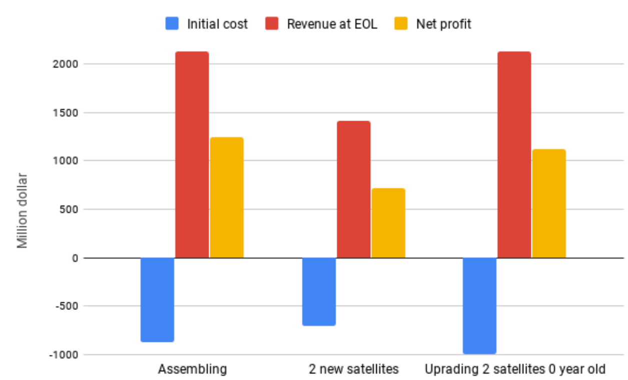


Fig. 4. Profit comparison between assembling and launching new satellites

As just shown, the services have been made captivating, from the costumers point of view and at the same time profitable for this venture, how is explained in the following section.

### D. Business Model

*a) Introduction:* The Business Model is shown highlighting the evolution of some key parameters through the 15 years service time. Numerical values will be given for some years only, both for Income and Financial Statements, when it is worth to highlight particular variations in the trends, otherwise all the results will be provided in figures 5 and 6. All the quantities mentioned are million dollars.

*b) Annual Detailed Results:* A brief analysis for *Year 0* is reported in Tables X and XI. Note that, as previously stated,

TABLE X
INCOME STATEMENT, YEAR 0

| Description | Category | Category Amount | Updated Value |
|---|---|---|---|
| Equity | Status | 7000 | 7000 |
| Missions | Income | 0 | 7000 |
| Investors | Income | 6000 | 13000 |
| Missions | Cost | 0 | 13000 |
| Annual | Cost | 0 | 13000 |
| Amortized | Cost | 0 | 13000 |
| Pay Investors | Cost | 0 | 13000 |
| Taxes | Cost | 0 | 13000 |
| Equity | Variation | +6000 | 13000 |
| Debts | Variation | +7200 | 7200 |

TABLE XI
FINANCIAL STATEMENT, YEAR 0

| Description | Category | Category Amount | Updated Cash |
|---|---|---|---|
| Cash | Status | 7000 | 7000 |
| Missions | Income | 0 | 7000 |
| Investors | Income | 6000 | 13000 |
| Missions | Cost | 0 | 13000 |
| Annual | Cost | 0 | 13000 |
| Fixed | Cost | 11711 | 1289 |
| Pay Investors | Cost | 0 | 1289 |
| Taxes | Cost | 0 | 1289 |
| Cash | Variation | -5711 | 1289 |

all the initial costs are assumed as fixed and sustained, on the financial point of view, at *Year 0*. Furthermore, all the money coming from investors is assumed turning into equity, because it is spent to build the initial assets and knowledge, therefore money going first into the initial capital and then internally invested.

What happens in *Year 1* is reported in Tables XII and XIII. The situation is more or less the same for the following years, with the only exception of the continuously decreasing mission costs (due to the learning factor) and the higher income from *Year 3* on (due to the beginning of the assembly service).

It is worth to take a look to year 12 and 13, when the debts to the investors is terminated (Tables XIV, XV for *Year 12* and XVI, XVII for *Year 13*): The key quantity evolution throughout all the service time are reported in Figures 5 and 6, for Income Statement and Financial Statement respectively.

*c) Final Values:* Finally, it is possible to highlight the final values of the business. They are summarized in table XVIII, whereas the indexes are reported in table XIX. Note that the values reported for *Small Company* and *Corporate* are directly the correspondent Equity fractions.

TABLE XII
INCOME STATEMENT, YEAR 1

| Description | Category | Category Amount | Updated Value |
|---|---|---|---|
| Equity | Status | 13000 | 13000 |
| Missions | Income | 2500 | 15500 |
| Investors | Income | 0 | 15500 |
| Missions | Cost | 811 | 14689 |
| Annual | Cost | 602 | 14007 |
| Amortized | Cost | 781 | 13226 |
| Pay Investors | Cost | 600 | 12626 |
| Taxes | Cost | 313 | 12313 |
| Equity | Variation | -687 | 12313 |
| Debts | Variation | -600 | 6600 |

TABLE XIII
FINANCIAL STATEMENT, YEAR 1

| Description | Category | Category Amount | Updated Cash |
|---|---|---|---|
| Cash | Status | 1289 | 1289 |
| Missions | Income | 2500 | 3789 |
| Investors | Income | 0 | 3789 |
| Missions | Cost | 811 | 2978 |
| Annual | Cost | 602 | 2376 |
| Fixed | Cost | 0 | 2376 |
| Pay Investors | Cost | 600 | 1776 |
| Taxes | Cost | 313 | 1463 |
| Cash | Variation | +174 | 1463 |

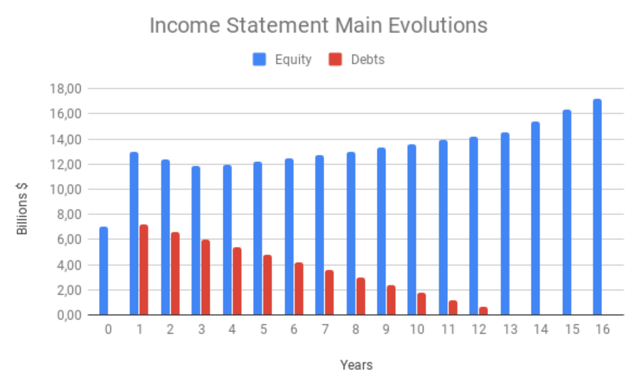


Fig. 5. Income Statement Key quantity evolution

## E. Off-Nominals

In this part of the report only the Off-Nominal cases will be presented, together with their economical/logistical impact, labelled with numbers. All the numbers already specifically mentioned (incomes and cost categories) will not be repeated. They can be found in sections III-B and /addrefforincomes/.

1) Logistics Group Off-Nominal situation: a fast come back from GEO is needed, with the consequence of a new Mission Module (with a cost of roughly 625 million dollars) needed in orbit as soon as possible and the production of a new backup copy.
2) Vehicle Group Off-Nominal situation: a launch is

TABLE XIV
INCOME STATEMENT, YEAR 12

| Description | Category | Category Amount | Updated Value |
|---|---|---|---|
| Equity | Status | 14199 | 14199 |
| Missions | Income | 3125 | 17324 |
| Investors | Income | 0 | 17324 |
| Missions | Cost | 449 | 16875 |
| Annual | Cost | 602 | 16273 |
| Amortized | Cost | 781 | 15492 |
| Pay Investors | Cost | 600 | 14892 |
| Taxes | Cost | 391 | 14501 |
| Equity | Variation | +302 | 14501 |
| Debts | Variation | -600 | 0 |

TABLE XV
FINANCIAL STATEMENT, YEAR 12

| Description | Category | Category Amount | Updated Cash |
|---|---|---|---|
| Cash | Status | 11100 | 11100 |
| Missions | Income | 3125 | 14225 |
| Investors | Income | 0 | 14225 |
| Missions | Cost | 449 | 13776 |
| Annual | Cost | 602 | 13174 |
| Fixed | Cost | 0 | 13174 |
| Pay Investors | Cost | 600 | 12574 |
| Taxes | Cost | 391 | 12183 |
| Cash | Variation | +1083 | 12183 |

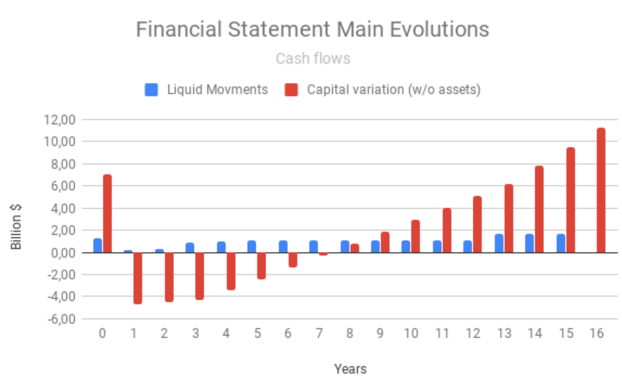


Fig. 6. Financial Statement Key quantity evolution

aborted, with the consequences of re-scheduling the mission, sustaining twice the mission costs and getting incomes one time only, paying the loss of income caused to the customer (20 to 40 million dollars, depending on the actual profitability of the satellite to be served and the kind of service requested).

3) Mission not performed (not even launched): re-scheduling is needed, as well as paying the loss of income caused to the customer (again 20 to 40 million dollars under the same considerations done before).
4) One of the modules supposed to stay in orbit is destroyed: there is the need to launch the backup copy as soon as possible (100 to 125 million dollars of launch cost), so that the service can continue, and to produce a new backup copy (variable costs from 300 to 625 million dollars depending on which module has been destroyed).
5) The customer satellite is destroyed while performing the service: there is the need to pay back both the loss of income caused to the customer (up to 40 million dollars per year of service left, depending on the remaining lifetime and the actual profitability of the satellite) and the amortized value for the satellite (assuming an average lifetime of 15 years and a cost of 300 million dollars, the value of the satellite to pay to the customer is 20 million dollars per year of service left, actualizing the amount with a proper inflation rate; an average served satellite is expected to be 10 years old, therefore with a value of 100 million dollars, that actualized with an inflation rate of 2% become 125 million dollars to pay to the customer).

TABLE XVI
INCOME STATEMENT, YEAR 13

| Description | Category | Category Amount | Updated Value |
|---|---|---|---|
| Equity | Status | 14501 | 14501 |
| Missions | Income | 3125 | 17626 |
| Investors | Income | 0 | 17626 |
| Missions | Cost | 447 | 17179 |
| Annual | Cost | 602 | 16579 |
| Amortized | Cost | 781 | 15798 |
| Pay Investors | Cost | 0 | 15798 |
| Taxes | Cost | 391 | 15407 |
| Equity | Variation | +906 | 15407 |
| Debts | Variation | 0 | 0 |

TABLE XVII
FINANCIAL STATEMENT, YEAR 13

| Description | Category | Category Amount | Updated Cash |
|---|---|---|---|
| Cash | Status | 12183 | 12183 |
| Missions | Income | 3125 | 15308 |
| Investors | Income | 0 | 15308 |
| Missions | Cost | 447 | 14861 |
| Annual | Cost | 602 | 14259 |
| Fixed | Cost | 0 | 14259 |
| Pay Investors | Cost | 600 | 13659 |
| Taxes | Cost | 391 | 13268 |
| Cash | Variation | +1085 | 13268 |

## IV. DISCUSSION

### A. Why humans?

There is no question that this project would be cheaper, less complex, and faster to execute if there were no humans involved. Today's robots are capable of performing the *majority* of tasks that humans can, and *sometimes* even better. The emphasis is on the words in italic. For certain tasks, the use of humans is still the best approach. The satellites in GEO

TABLE XVIII
BUSINESS RESULTS

| Description | Category | Initial | Final | Result |
|---|---|---|---|---|
| Equity | Variation | 7000 | 17200 | +145.9% |
| Small Company | Variation | 1000 | 2459 | +145.9% |
| Corporate | Variation | 6000 | 14741 | +145.9% |
| Investors | Variation | 6000 | 7200 | +20% |

TABLE XIX
INCOME STATEMENT RESULT

| Description | Category | Value |
|---|---|---|
| ROE | Income Statement | 2.46 |
| ROI | Income Statement | 1.32 |
| Pay Back Time | Investors | 11.3 years |

today were not designed to be physically interacted with after deployment as the designers of the time would have had to spend extra time making their satellites accessible. For this reason, programming a robotic arm, or even using an advanced Machine Learning algorithm, would not be able to execute the mission. There are plenty of unknowns in a mission of this nature - the blueprints of the satellite might be useless after the space environment has taken its toll on the satellite. Humans are capable of improvising and making on-the-spot decisions much better in such a scenario, meaning that even if using humans adds to the complexity and cost of the project, using humans is the only option.

### B. Group Collaboration

As mentioned in Section II, having an Overall Systems Budget to compile all key parameters allowed the project's progress to be tracked. Towards the end of the project, when values began to converge towards a consistent system of numbers, the sub-teams could begin finalising their work. This iterative approach is widely-used in industry for projects of much greater complexity. Keeping team members updated in virtually real-time showed itself to be important and manageable using the Overall Systems Budget.

### C. Cost analysis

*a) Modules cost:* The results given by each methods for the development and the production costs of modules for 80 missions are varying in a very large range from $ 15 billion to $ 45 billion. This large range proves the difficulty to estimate costs for such a program. Those different methods are not all equivalent and are probably more adapted for existing missions. As the servicing mission proposed in this study is very different from existing program, it's acceptable to use different models, and the results (even if quite different) give probably an accepted range for the module costs.

*b) Initial costs:* The critical costs to be estimated and to start this program is probably the development cost for modules. Results from method 1 and method 3 shows that this development cost is almost half of the total cost for the program cost effort for the modules. In comparison the actual production cost and launches are not critical.

*c) Mission costs:* Mission costs could be optimized to better take into account the duration of the program. If the modules costs are taking into account the mission repeatably, it is not the case for other costs. For example, for each mission one launch need to be provided. A call for bids for launch will be made and as their is a known and high number of launches requested, the price for launches will be negotiate between the servicing company and company responsible for launch, thus the cost per launch will probably be smaller that the one presented here.

*d) Annual costs:* The costs presented in Table IX for the first year are here to give a ROM to the reader of what should be taken into account to start a space servicing business. Training and ground facilities costs has been estimated by the writers of the study and could probably be improved in future studies. The training costs could have been included in the global cost for facilities.

### D. Price Evaluation

The results in net profit significantly depend on how old the satellite is, especially when an upgrade is performed. For the costumer, this specific service starts to be more profitable than launching a new satellite only if performed when the satellite is no older than 7 years and net profit grows as the upgrading is performed earlier in satellite's lifespan cause it will have more time to take advantage of its increased revenue. The range varies from a minimum of $ 16 million if the satellite is 7 years old until a peak of $ 470 when the satellite is brand new.

The same can be said for the the Refuelling & Upgrading service. Here, there is not a minimum age to be profitable but still the range varies from $ 156 million for a satellite at its EOL until a maximum of $ 600 million for a 7 year old satellite.

Another important aspect to consider is that the net profit presented via comparing values from different time frames. A clear example is given from a refuelled satellite that is going to last other 10 years compared to a new satellite that is going to last 15. The profits has been considered at EOL so the values are reliable but what is not been considered is that in the first case, the customer will need to launch a new spacecraft in 10 years instead of 15 as in the second scenario.

### E. Business Model

The whole discussion can be performed by looking at the two graphs (Figures 5 and 6) together.

One can see that, despite slightly positive cash incomes, from *Year 1* to *Year 3* the Equity value decreases. This is mainly due to the service prices set to the long term, taking into account the cost reduction coming from the learning factor. The amortized initial cost plays a key role in this analysis, because it would not be possible to see this trend by looking to the Financial Statement only. About the Income Statement only (Figure 5), looking at the final Equity value it is possible to see that it gets more than doubled, proving the profitability of the business.

Considering finally the Financial Statement only (Figure 6), the cash flows are always positive, which means that the business is sustainable itself, without the need of further capital injections (apart from the initial investment). Moreover, at the end of the service an high value of cash is available, meaning that the actual incomes could potentially have been spread in dividends quite safely. It is however safer to always keep a certain amount of money as internal cash available, to face unforeseen situations (as one can see when studying the Off-Nominal cases, for example).

### F. Off-Nominals

The solutions to the Off-Nominal situations presented in section III-E are reported here, with the correspondence of the labels.

1) It is possible to build a new backup copy of the Mission Module by paying its cost. A new launch has to be scheduled, but this is not critical on the logistic point of view, because it can be done within $4$ weeks, since everything that needs to be launched is ready. In total the cost to be sustained is more or less $30\%$ of the annual profit, so still affordable without affecting either the business or future services.
2) The costs for one more mission to be sustained are again below the average annual profit, as well as the very minor impact of the loss of income caused to the customer, so they can be endured. On the logistic point of view, the free launch slot available in one year can be exploited to re-schedule the mission directly then, without the need to hurry and schedule an immediate backup launch.
3) The impact here is almost purely logistical (as previously proved the economical impact of the need to pay the loss of income is very minor), and as stated for the right previous case the free slot can be exploited to re-schedule the mission again then.
4) Similarly to what presented for the case from Logistics Group, there is the need to launch the backup copy and re-build one of the destroyed module. Costs are variable, depending on what module has been destroyed, but up to the already presented $30\%$ of the annual profit in the worst case scenario of the Mission Module (the most expensive one) destroyed. What already said about the time needed to schedule and perform the backup launch in that very same case is still valid here.
5) The total amount to be paid to the customer has the order of magnitude of $250$ to $350$ million dollars, which is lower than the case of the need to produce again the Mission Module, so it can be faced without any particular issue.

There are a couple of considerations which are valid for all the aforementioned cases, which can be considered as a global Off-Nominal strategy:

- Keep a launch slot free and ready to be used in case of need
- Keep cash available to be always able to pay the consequences of an unexpected situation, even without the need of a particular insurance.

About this last point, one can easily see that, if all the presented Off-Nominal situations had to happen, the total cost to face would be in the order of $1700$ million dollars. This means that a good safety strategy is to always have that cash available, keeping it liquid inside the company by retaining a fraction of the eventual dividends. One can also see that, apart from the first year of service when it is "just" more or less $300$ million dollars below that level, this amount is always available with the Business Model presented here, proving now also the robustness of the same.

### G. Social and Political Considerations

As with all completely new projects, potential societal and political impacts must be considered. As the project is of a commercial nature, there is no dependence on government budgets, which are known to be influenced somewhat by public opinion. By not relying on any one government's political agendas, the project has the autonomy to use its money in the best interests of the business. Furthermore, there is currently a lack of legal jurasdiction in space other than the Outer Space Treaty, which is not even recognised by all nations - meaning that there would not be any technicality issues with sending humans to GEO.

### H. Forward-looking Perspective

As the market for upgrading satellites grows and evolves, so too will this project. Changes will have to be made in the business plan as the needs of customers changes. The main agent of change in the future is forecast to be the construction of satellites which are designed to be upgradeable/repairable using robots designed by the same company. This would reduce the number of potential customers over time and require a fresh outlook on the GEO satellite upgrading market. Nonetheless, from circa 2030-2045, there is expected to be a market for such services, allowing for a sustainable growth as projected by the financial aspects of this report. By taking care of the existing infrastructure in space rather than constantly sending new satellites, mankind can maintain a sustainable and responsible presence in GEO, without adding to the vast amounts of space debris in the graveyard orbit.

## V. Conclusion

A first feasibility study of a service of this kind has been performed, looking particularly into its economical part, providing some first estimates about costs, pricing and business plan.

Wrapping up the results and the discussion, one can see that the initial goal of studying and proving the feasibility of the service has been reached, remaining consistent to costs and typical prices coming from the history of spaceflight. Numbers coming from the three cost analysis methods seem however to be quite different, even though Method 1 is the only one having data from literature detailed enough to build a business model on it. A deeper research, not limited to history only but also getting data from actual companies and agencies, would be needed to build the final detailed and feasible model, because as one can see the costs coming from the different methods are far from being similar one another. In any case, the structure of the business model wouldn't change, pricing, loans and the key numbers of the economical strategy would just need to be reviewed according to the final magnitude of the costs.

Robustness of the service has also been proved, showing clearly that off-nominal situations barely affect the activities, both in the economical and operational (meaning the impact on future missions) point of view. Satellites in the future will perhaps be built to be served, a factor that can lead to an higher need of services of this kind. New technologies and strategies will be available by then, with the consequence for the providers of the need to keep studying and innovating this service. Refuelling, upgrading and assembling are anyway a good starting point and training base for the logistics, leaving the possibility to upgrade just the service offered to new and, for now, unthinkable perspectives.

## VI. Division of work

Julie worked on the cost analysis. During the oral presentation, she presented costs obtained with method 1, but in order to support the analysis, she worked on two other methods to test the first one. Even if the results are quite different, it is still interesting to show the reader the variability of a cost estimation at this stage of the program, when using different cost estimation methods. More accurate cost estimation could mix those estimation (using the most accurate model for each modules).

Alessandro worked on the communication channels, the Business Model and the economical analysis of the off-nominal cases. During the oral presentation, he presented the Business Model and the off-nominal cases, but those have been tackled group-wise on the solution strategy point of view.

Matija worked on creating and managing the Overall System Budget, on investigating why humans are required for the mission, as well as collaborating with the Vehicle group to ensure the design was economically viable. During the oral presentation, he opened for the whole Red Team and presented a general overview of the mission.

Stefano worked on the introduction and price estimation, investigating the feasible margin profit from costumers and project points of view. He worked with the Service group to ensure the economical viability of the decided services. During the oral presentation, he presented the price estimation, the conclusion and some future perspectives.

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## VII. Appendix

### A. Parameters values for AMCM

### B. Modules presentation for cost analysis

### C. Modules detailed cost for Method 1

### D. Modules detailed cost using Method 2

### E. Modules detailed cost using Method 3

TABLE XX
PARAMETERS FOR AMCM [8]

| Parameter | Value |
|---|---|
| $\alpha$ | $9.51 \cdot 10^{-4}$ |
| $\beta$ | 0.5941 |
| $\Xi$ | 0.6604 |
| $\delta$ | 80.599 |
| $\epsilon$ | $3.8085 \cdot 10^{-55}$ |
| $\Phi$ | -0.3553 |
| $\gamma$ | 1.5691 |

| | Mission Service Module | Mission Module | Airlock | Storage Module | Launch Reentry Vehicle | Heat shield LRV | LEV Service Module | MSM / LSM Propulsion | Storage Module Propulsion |
|---|---|---|---|---|---|---|---|---|---|
| | *MSM* | *MM* | *AL* | *StoM / SM* | *LEV* | *HS LEV* | *LSM* | MSM / LSM Prop | *SM Prop* |
| **Structural Mass [kg]** | 900 | 6500 | 3500 | 4600 | 3500 | 1500 | 900 | 100 | 100 |
| **Payload Mass [kg]** | 0 | 3000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Fuel Mass [kg]** | 3000 | 500 | 0 | 5000 | 1000 | 0 | 4000 | 0 | 0 |
| **Total Mass [kg]** | 3900 | 10000 | 3500 | 9600 | 4500 | 1500 | 4900 | 100 | 100 |
| **Fuel Type** | $MMH/N_2O_4$ | $N_2$ | / | Xenon | $MMH/N_2O_4$ | / | $MMH/N_2O_4$ | / | / |
| **Fuel Price ($/kg)** | 10 | 1 | 0 | 15 | 10 | 0 | 10 | 0 | 0 |
| **Number of missions** | 1 | 90 | 90 | 90 | 10 | 1 | 1 | 1 | 90 |
| **Quantity** | 75 to 90 | 2 | 2 | 2 | 9 | 75 to 90 | 75 to 90 | 150 to 180 | 8 |

Fig. 7. Vehicle Design group modules, with fuel and quantity

| | Mission Service Module | Mission Module | Airlock | Storage Module | Launch Reentry Vehicle | Heat shield LRV | LEV Service Module | MSM / LSM Propulsion | Storage Module Propulsion |
|---|---|---|---|---|---|---|---|---|---|
| | *MSM* | *MM* | *AL* | *StoM / SM* | *LEV* | *HS LEV* | *LSM* | MSM / LSM Prop | *SM Prop* |
| **Development Cost per Mass unit ($K/kg)** | 698 | 698 | 698 | 698 | 698 | 698 | 698 | 1500 | 1500 |
| **Production Cost per Mass unit ($K/kg)** | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 33 | 33 |
| **Complexity factors** | 0,2 | 0,8 | 0 | 0,2 | 0,2 | 0 | 0,2 | 0 | 1 |
| **Development Cost ($K)** | $ 125 640 | $ 5 304 800 | $ - | $ 642 160 | $ 488 600 | $ - | $ 125 640 | $ - | $ 150 000 |
| **Fabrication Cost for FU ($K)** | $ 49 500 | $ 522 500 | $ 192 500 | $ 253 000 | $ 192 500 | $ 82 500 | $ 49 500 | $ 3 300 | $ 3 300 |
| **Initial cost** | | | | | | | | | |
| **Development Cost ($K)** | $ 125 640 | $ 5 304 800 | $ - | $ 642 160 | $ 488 600 | $ - | $ 125 640 | $ - | $ 150 000 |
| **Fabrication Cost ($K)** | | $ 1 045 000 | $ 385 000 | $ 506 000 | | | | | $ 26 400 |
| **Additional cost for the 1st mission** | | | | | | | | | |
| **Fabrication cost ($K)** | $ 49 500 | | | | $ 192 500 | $ 82 500 | $ 49 500 | $ 3 300 | |
| **Fuel cost ($K)** | $ 30,0 | $ 0,5 | | $ 75,0 | $ 10,0 | | $ 40,0 | | |

Fig. 8. Development costs and first unit fabrication costs for modules using Method 1

| | Mission Service Module | Mission Module | Airlock | Storage Module | Launch Reentry Vehicle | Heat shield LRV | LEV Service Module | LSM / MSM Propulsion | Storage Module Propulsion |
|---|---|---|---|---|---|---|---|---|---|
| | *MSM* | *MM* | *AL* | *StoM / SM* | *LEV* | *HS LEV* | *LSM* | *LSM Prop* | *SM Prop* |
| **Structural Mass [kg]** | 900 | 6500 | 3500 | 4600 | 3500 | 1500 | 900 | 100 | 100 |
| **Payload Mass [kg]** | 0 | 3000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **AMCM Model Parameters** | | | | | | | | | |
| **M [kg]** | 900 | 9500 | 3500 | 4600 | 3500 | 1500 | 900 | 100 | 100 |
| **Q** | 80 | 2 | 2 | 2 | 9 | 80 | 80 | 160 | 8 |
| **S** | 2,13 | 2,13 | 2,13 | 2,13 | 2,27 | 2,27 | 2,13 | 2,13 | 2,13 |
| **IOC** | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 |
| **B** | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 1 |
| **D** | 0 | 0 | -2 | 0 | 0 | -2 | 0 | -2 | 2,5 |
| **Estimated cost for modules development and production cost** | | | | | | | | | |
| **$K FY 1999** | $ 5 031 088 | $ 2 665 539 | $ 437 665 | $ 1 651 131 | $ 6 228 143 | $ 4 138 089 | $ 5 031 088 | $ 565 021 | $ 925 778 |
| **$K FY 2010** | $ 6 587 069 | $ 3 489 918 | $ 573 023 | $ 2 161 782 | $ 8 154 341 | $ 5 417 889 | $ 6 587 069 | $ 739 767 | $ 1 212 096 |

Fig. 9. Development and production cost for modules using Method 2 (cost for 80 missions)

| | Mission Service Module | Mission Module | Airlock | Storage Module | Storage Module Propulsion | Launch Reentry Vehicle | Heat shield LRV | LEV Service Module | LEV Service Module Propulsion |
|---|---|---|---|---|---|---|---|---|---|
| | *MSM* | *MM* | *AL* | StoM / SM | SM Prop | LEV | HS LEV | LSM | LSM Prop |
| **M (kg)** | 900 | 9500 | 3500 | 4600 | 100 | 3500 | 1500 | 900 | 100 |
| **M (pounds)** | 1984,16 | 20943,92 | 7716,18 | 10141,27 | 220,46 | 7716,18 | 3306,93 | 1984,16 | 220,46 |
| **Q** | 80 | 2 | 2 | 2 | 8 | 8 | 80 | 80 | 160 |
| **Dev ka** | 1457,7 | 1457,7 | 1457,7 | 1457,7 | 29,125 | 285,57 | 285,57 | 1457,7 | 29,125 |
| **Dev b** | 0,0856 | 0,0856 | 0,0856 | 0,0856 | 0,4554 | 0,2667 | 0,2667 | 0,0856 | 0,4554 |
| **FU ka** | 46,624 | 46,624 | 46,624 | 46,624 | 1,865 | 49,923 | 49,923 | 46,624 | 1,865 |
| **FU b** | 0,2146 | 0,2146 | 0,2146 | 0,2146 | 0,4782 | 0,2409 | 0,2409 | 0,2146 | 0,4782 |
| **Development cost ($M)** | $ 2 792,16 | $ 3 416,26 | $ 3 136,39 | $ 3 210,63 | $ 339,95 | $ 3 108,01 | $ 2 479,38 | $ 2 792,16 | $ 339,95 |
| **First unit cost ($M)** | $ 200,72 | $ 332,84 | $ 268,64 | $ 284,86 | $ 16,87 | $ 356,51 | $ 290,68 | $ 200,72 | $ 16,87 |
| **Learning rate power** | 0,765534746 | 1 | 1 | 1 | 0,925999419 | 0,925999419 | 0,765534746 | 0,765534746 | 0,765534746 |
| **Production cost for Q units ($M)** | $ 5 747,40 | $ 665,67 | $ 537,27 | $ 569,73 | $ 115,70 | $ 2 445,27 | $ 8 323,43 | $ 5 747,40 | $ 821,12 |
| **Total ($M) FY 2012** | $ 8 539,56 | $ 4 081,93 | $ 3 673,66 | $ 3 780,35 | $ 455,66 | $ 5 553,29 | $ 10 802,82 | $ 8 539,56 | $ 1 161,08 |
| **Total ($M) FY 2010** | $ 8 110,66 | $ 3 876,91 | $ 3 489,15 | $ 3 590,48 | $ 432,77 | $ 5 274,37 | $ 10 260,24 | $ 8 110,66 | $ 1 102,76 |

Fig. 10. Development and production cost for modules using Method 3 (cost for 80 missions)