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Suborbital Space Tourism – A Commercial Feasibility Assessment

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Abstract

This paper provides an analysis of the commercial feasibility of the suborbital tourism market while considering the large uncertainties in the demand. Deciding whether to enter this market or not, and more generally deciding which commercial strategy to choose, becomes an even greater challenge in the face of these large uncertainties. Since it is unlikely that future demand forecasts will be significantly more precise, an analysis which takes these uncertainties into account is needed. Our work addresses this problem by using a Monte Carlo Simulation to calculate the distribution of possible results in commercial terms (net present value (NPV) developed from a discounted cash flow analysis). By conducting a sensitivity analysis, we identify the most impactful factors in development and create a probability distribution of their uncertainties. We implement several decision rules to simulate five different commercial strategies a company in this sector might have. Previous work done by the authors defined a design space of 33 suborbital vehicle architecture and optimized these with respect to mass and risk. We choose optimal architecture #4 with one pilot for the purpose of this paper, which is the same architecture as XCOR's Lynx. Data from studies such as those by the Tauri Group and Futron are used to model the distribution of the demand and its uncertainty. The cost model is mainly based on cost estimation relationships from Koelle. We found that there are two dominant commercial strategies: a riskier one with an aggressive fleet expansion with a large vehicle (16 participants, average expected NPV is $2.8 billion, 41 % chance of incurring losses), and a less risky one with a neutral fleet expansion and a medium vehicle (4 participants, average expected NPV is $2 billion, 33 % chance of incurring losses). We conclude that the suborbital tourism market can probably be made commercially attractive by proper management of development even in the face of significant uncertainty.

Keywords: System architecture, suborbital tourism, uncertainty analysis, discounted cash flow, Monte-Carlo simulation, target curves

1. Introduction and summary of the market demand

The Suborbital Space Tourism Industry is characterized by the commonly understood requirement of taking tourist to 100 km to provide them an adventures experience. This experience includes a few minutes of weightlessness time and the observation of the curvature of the earth. This industry is part of the so-called New Space, in which private investors invest money to receive a desirable future return on investment. This is a paradigm change to previous government funded activities in the space sector. Since around 80% of the suborbital space revenues are expected to be made by ticket sales to tourists [4], knowledge of the demand depending on the ticket price is crucial to justify the investment in the development of such vehicles. But there is great uncertainty in the demand, casting doubts for all but the most intrepid investors.

The objective of this paper is to study the commercial feasibility of such an endeavor including these great uncertainties. There has been done a market study from the Futron group back in 2002 [1]. They surveyed 450 people with an annual income of at least $250,000 about their interest in space tourism and willingness to purchase a ticket for $100,000. Based on this data, the report filtered the worldwide population to get the fraction of people who might be interested in taking these flights once available. A Fisher-Pry curve with a 40-year market maturity was used to model the market diffusion. Assuming 2006 to be the most plausible start year of suborbital flights, they predicted 15,000 passengers for 2021. Four years later in 2006 the Futron Corporation published an updated report [2]. They lowered their forecast from 15,000 to 13,000 passengers for 2021 as three major changes were made to adapt the prediction to better reflect the state of the suborbital space tourism industry in that year:

- The plausible start date was moved from 2006 to 2008
- The initial ticket price raised from $100,000 to $200,000 (for the first three years, then declining to $50,000 by 2021)
- However, the growth in high net worth population has recovered from 2002 to 2006, resulting in a small increase of target population.

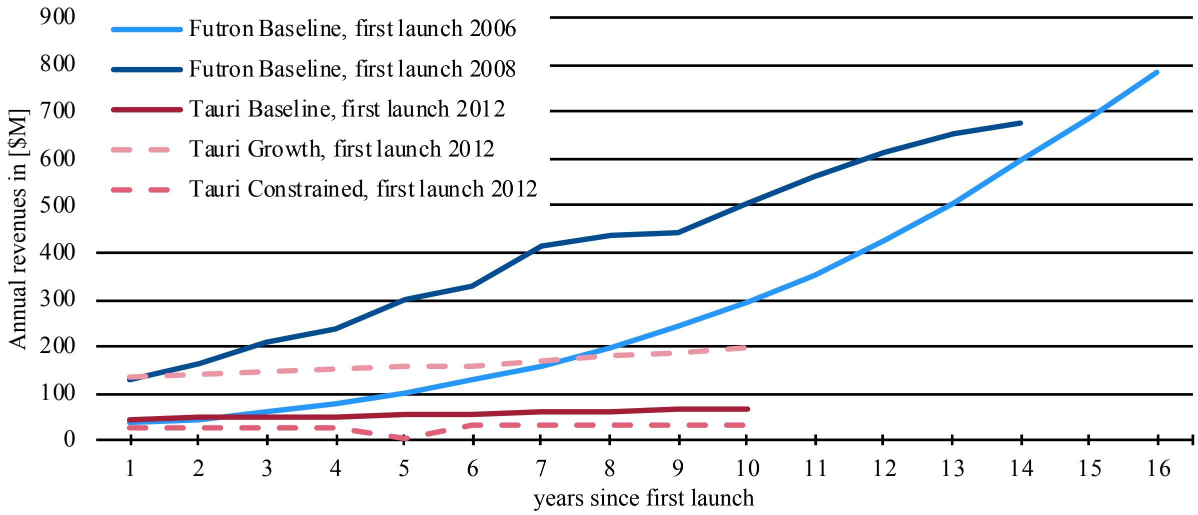

Fig. 1: Comparison of several forecasts of Futron [1, 2] and the Tauri Group [3, 4]

For the last year, 2016, the report predicts an annual passenger demand of 4,400 for a ticket price of $100,000. The 10-year market demand forecast from the Tauri Group has included a price elasticity curve [3, 4]. The relationship was developed for individuals with at least $5 million in investable assets. Their predicted demand for a ticket price of $100k was 4,400 passengers. The Tauri group investigated three different scenarios, a low constraint demand, a baseline, and a high demand growth scenario. An overview of the revenue forecasts is shown in Fig. 1.

As of the date of writing this paper, no commercial suborbital spaceflight has taken place and therefore revenues in the market remained zero. This comparison shows how uncertain the forecasts about the revenue of the market are (revenues here as a proxy for demand). However, for a valuable commercial assessment, not only the demand as an absolute value has to be characterized, but also its high uncertainty. This high variation is not bad per se. If flexibility can be implemented into the system, it can limit the downside risk (if demand is lower than expected), but can also make use of the upside chance if demand is above the average expectation [5].

In previous work, we addressed the question about what system architecture of suborbital space tourism vehicles will provide the best combination of performance, cost and safety [6, 7]. We showed that the architecture of a suborbital tourism vehicle is depicted by a set of coupled decisions. These are about the form of the vehicle itself and are shown in Table 1 (colored options are our proposed vehicle #4). A full unconstraint enumeration would lead to 2,048 different architectures, but not all of them are feasible. After applying constraints, the number reduces to 33. This design space was optimized using a parametric model with an iso-performance approach (fixed altitude of 100 km and fixed number of participants). The cost dimension was approximated by the launch mass and the safety was quantified by using a metric based on a hazard list with associated severities and likelihood factors. Six non-dominated architectures could be identified that merit a more refined design analysis [6, 7].

Table 1: Architectural decisions with colored alternative being our choice of the optimal architecture based on previous work

		Decision	Alt. 1	Alt. 2	Alt. 3	Alt. 4	# of option
		nModules	1	2			2
Module 1	Launching	Take-off mode 1	Horizontal	Vertical			2
Module 1	Flying	Wing 1	No	Yes			2
Module 1	Flying	Jet Engine 1	No	Yes			2
Module 1	Flying	Rocket Engine1	No	Yes			2
Module 1	Landing	Landing mode 1	Gliding	Hor. Powered	Parachute	Rocket	4
Module 2	Flying	Wing 2	No	Yes			2
Module 2	Flying	Rocket Engine 2	No	Yes			2
Module 2	Landing	Landing mode 2	Gliding	Parachute	Rocket	None	4

Given his results and for the sake of this paper, we further downselect from 6 non-dominated pareto architectures to a single architecture, for which we build a parametric cost model and assess the potential profitability of the suborbital space tourism market. We choose optimal architecture #4 since it is in the “knee” of the pareto front with a low risk, and relatively small launch mass (the financial analysis could have been done for any architecture, but as turns out later the choice of physical architecture has little influence on the overall financial feasibility). This architecture is closest to XCOR’s Lynx, but with four participants instead of 1 participant in XCOR's vehicle. Our choice is a winged single-stage vehicle with a rocket engine and no jet engine. It launches horizontally and lands horizontally unpowered. Furthermore, it has one pilot and a LOX/LH2 rocket engine. This architecture is represented by the colored options in Table 1.

The specific objective of the paper is to combine the technical performance information for sub-orbital vehicles [6, 7] with a cost model and an uncertain market demand model to generate a set of possible economic results using a discounted cash flow analysis in combination with a Monte Carlo simulation.

In the remaining part of this paper, the models are described in the following section 2, where we first develop a surrogated mass model as a function of the number of participants (section 2.1). Based on this we use cost estimation relationships (CER) to develop a cost model as a function of the number of participants (section 2.2). The demand side is model by the market model in section 2.3. In section 3, five different commercial strategies are defined. In the result section 4, we first show a sensitivity analysis to identify the most impactful parameters, followed by a comparison of the five commercial strategies, before we conclude in section 5.

2. Models

An overview of our approach is shown in Fig. 2, which serves as an outline of the next remainder of this paper. Specifically, we build a surrogate model of the vehicle to obtain the mass as a function of the number of participants for a specific optimal architecture (the mass model, section 2.1). With this information, we enter into the cost model (section 2.2) and use mass-based Cost Estimation Relationships (CERs) techniques to estimate development costs c_{dev} and per flight cost $c_{perFlight} = c_{marginal}$ (which is a function of the number of participants n_{PAX}). Since the per flight cost model considers learning, this cost component depends additionally on the number of already flown flights $n_{flights}$. This information is fed back from the Monte-Carlo simulation module. The market model (section 2.3) consists of a pricing and a demand model. Both exchange information to define the ticket price P_{ticket} with a corresponding market size $n_{able+willing}$. The different strategies are defined in section 3 by a combination of number of participants per launch n_{PAX} and fleet expansion strategy (how aggressively additional vehicles are added to the fleet). The distribution of possible results (in terms of NPV) for five scenarios is compared in section 4.2. A complete list of the parameters used in the model is shown in Table 2. Default values and uncertainty ranges for those parameters are added in Table 7.

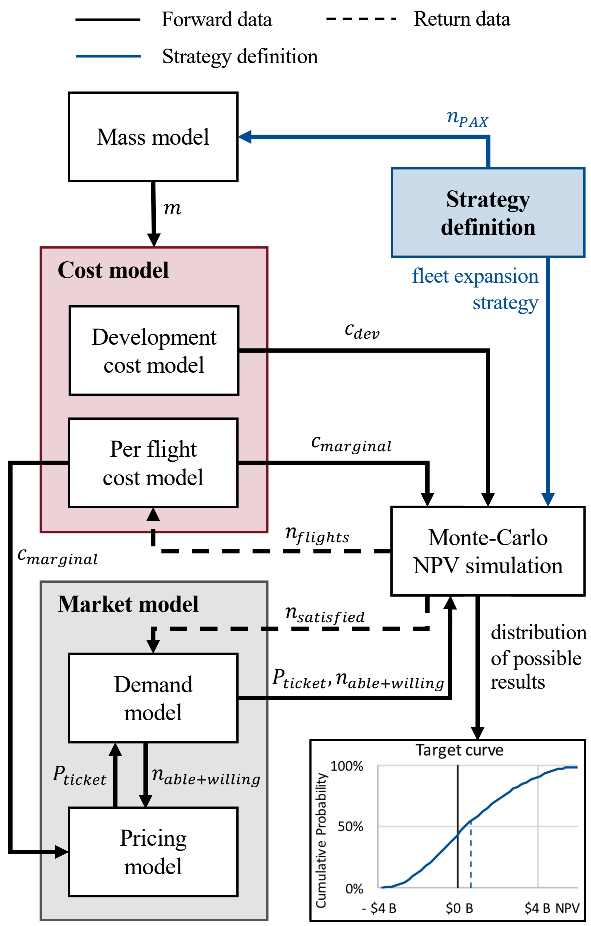

Fig. 2: Overview of the approach

Table 2: List of the parameters that are used in the model

Parameters
Business
Fraction of net worth spend on ticket (FoNW)
Market share captured by our project
Discount rate
Operational
Maximum launches per year per vehicle
Development time
Cost
Lifetime of rocket plane airframe
Lifetime of rocket engine
Learning curve factor for production
Learning curve factor for operation
Development costs airframe uncertainty range
Production costs airframe uncertainty range
Production costs rocket-engine uncertainty range
Variable operational costs uncertainty range

2.1 Mass model

As an outcome from this previous work, the optimized mass data for 1, 4, and 16 participants is available. The purpose of the mass model is to estimate the mass of the airframe, the rocket engine and the propellant for any given number of participants between 1 and 16 in a flight. This serves as an input for the cost estimation model, so that cost values are a function of the number of participants. Based on the available data, we generated a surrogated model for optimal architecture #4. From those mass components a functional relationship for the total mass can be derived. A linear regression was used as it shows best approximation.

The total mass is given in Eq. (1) as the sum of the airframe (AF) and rocket engine (RE) dry mass plus the propellant mass. The AF dry mass includes the participants as well as one pilot. All calculates values are in kilograms.

$$m_{tot} = m_{dry_{AF}} + m_{dry_{RE}} + m_{prop} \quad (1)$$

All functional relationships are valid in $n_{PAX} \in [1;\ 16]$ as the regression was done for data in this interval. No information about validity outside of the interval is available.

Airframe dry mass:

$$m_{dry_{AF}} = 1606 + 329 \cdot n_{PAX} \quad \text{for } n_{PAX} \in [1;\ 16] \quad (2)$$

Rocket engine dry mass:

$$m_{dry_{RE}} = 633 + 37.8 \cdot n_{PAX} \quad \text{for } n_{PAX} \in [1;\ 16] \quad (3)$$

Propellant mass (LH2 + LOX, where the O/F ratio is 2.3):

$$m_{prop} = 1497 + 147 \cdot n_{PAX} \quad \text{for } n_{PAX} \in [1;\ 16] \quad (4)$$

Total mass:

$$m_{tot} = m_{dry_{AF}} + m_{dry_{RE}} + m_{prop} = 3736 + 514 \cdot n_{PAX} \quad \text{for } n_{PAX} \in [1;\ 16] \quad (5)$$

The results of this mass model for the different sizes are shown in Table 3 as well as Fig. 3. Whereas the mass for the airframe has the steepest slope and therefore sensitivity with increasing number of participants, the rocket engine mass has a smaller marginal increase. The propellant mass is in-between those two lines. We can also see a strong effect of the economy of scale where the smallest vehicle has over 4 metric tons per participant, and the largest one has below 0.75 metric tons per participants.

Table 3: Results of the mass model with mass components of the airframe, the rocket engine, and the propellant mass. The dry mass includes one pilot and the participants. All values are in [kg]

n_{PAX}	$m_{dry_{AF}}$	$+ m_{dry_{RE}}$	$+ m_{prop}$	$= m_{tot}$
1	1,935	671	1,644	**4,250**
4	2,922	784	2,085	**5,791**
16	6,870	1,238	3,849	**11,957**

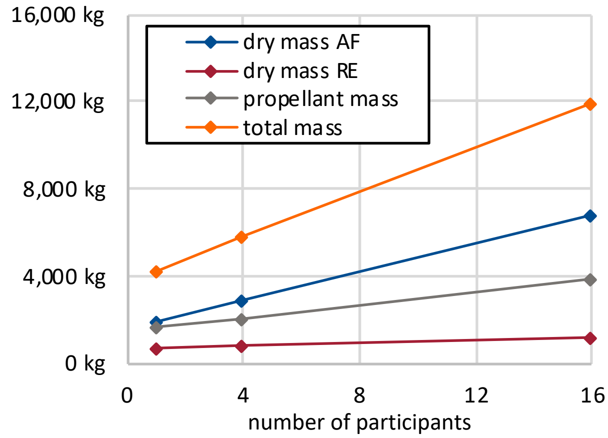

Fig. 3: Linear dependence of mass as a function of participants (Eqs. (2)-(5)). Mass values are in [kg]

2.2 Cost model

To assess the life-cycle cost of a vehicle, we decomposed it into development cost for the air frame (AF), the variable operating cost, fixed operating cost and costs for sales and administration (see first level of decomposition in Fig. 4). The model for each of those four contributions is described in the following subsections 2.2.1 - 2.2.4. The variable operating cost is further divided into launch operation, maintenance, amortization of production and propellant cost. These contributions of the second level of decomposition is described in Appendix A. The sum of those components is given by a master Eq. (8) in subsection 2.2.2

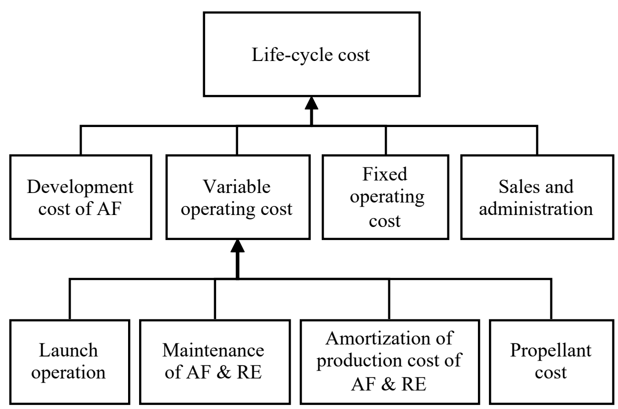

Fig. 4: cost model overview and breakdown

Some cost estimations are given for a general case as a function of the mass. By using the mass model developed in the previous section, this cost estimation equation can be easily rewritten as a function of the number of participants. Generally, this cost model can be applied to every suborbital vehicle architecture. However, in this paper we focus on the cost model for the optimal architecture #4. We developed Cost Estimation Relationships (CERs) for development and production costs of other suborbital airframes in [6]. We use several cost estimation techniques such as CERs, analogies, and real data to develop a parametric cost model of the vehicle. Specific CERs on suborbital vehicles are not available at the time of writing this paper. We therefore use the closed available cost estimations: orbital lunch vehicles and fast airplanes. Main source here is Koelle [8]. In most cases, suborbital vehicles are outside of the applicable range of the developed CERs due to their lighter dry mass. However, we will estimate the development costs based on these CERs and investigate the effect of the introduced error with a sensitivity analysis in a section 4.1.

2.2.1 Development costs

The development costs account for research, development, testing and evaluation (RDT&E) of the suborbital vehicle. In general, it can be broken down into development costs for the rocket engine and the airframe. In this paper, we assume that the engine is already developed and can be purchased from the market so only production costs incur. Not all of the development costs of the airframe are accounted for in a single year, but they are spread over a certain development time t_{dev} (baseline 5 years, but underlies an uncertainty as described later). We model the distribution in alignment to common distributions in the space sector [9]: 5% for the first year and then evenly spread out over the remaining time (e.g. for a 5 year development, 23.75% in years 2-5).

For the total development effort of the airframe, we use Koelle's CER [8]. It is given by Eq. (6) with the applicable mass range and a cost conversion value d that translates one work man year (WYr) to $ depending on the year and the country where the development takes place. This factor b equals $305,900 for 2017 in the US (detailed information on the derivation in [6], [8], and [10]). The CER is derived for government programs. Commercial activities have significantly lower costs. This is modeled by a commercial factor $f_{C_{AF}}$, which we chose here to be 0.5 [6, 8, 10].

$$c_{Development_{AF}}\left(\mathrm{m}_{\mathrm{dry}_{\mathrm{AF}}}\right) = 1420 \cdot m_{dry_{AF}}^{0.35} \cdot f_{C_{AF}} \cdot b \quad \text{for } m_{dry_{AF}} \in [7{,}000;\ 150{,}000]\ kg \qquad (6)$$

with

$c_{Development_{AF}}$:	Development cost for a rocket plane airframe (AF) in [$]
$c_{Development_{AF_{\#4}}}$:	Development cost for the architecture #4 rocket plane AF in [$]
$m_{dry_{AF}}$:	Dry mass of airframe without engines in [kg]
$f_{C_{AF}}$:	Commercial factor for a rocket plane airframe [-]; here 0.5
b:	Cost conversion value in [$/WYr]; $305,900/WYr in 2017 for the US

2.2.2 Variable operational costs

The variable operational costs consist of launch operation, maintenance, amortization and propellant costs. These four components are described in Appendix A, from where we can derive the total variable operational costs as a function of the number of participants n_{PAX}, number of produced airframes n_{AF}^{th} and rocket engines n_{RE}^{th}, and the number of already conducted flights n_{flight}^{th}. Eq. (7) shows this sum of the launch operation, maintenance, amortization and propellant costs with Eq. (8) displaying the marginal costs.

$$\begin{aligned} & c_{\mathrm{vOper_{tot}}}\left(\mathrm{n_{PAX}}, n_{AF}^{th}, n_{RE}^{th}, n_{flight}^{th}\ n_{LT_{AF}}, n_{LT_{RE}}\right) \\ &= \overbrace{c_{vOper_{LO}}\left(\mathrm{n_{PAX}}, n_{flight}^{th}\right)}^{\substack{per\ flight\ cost \\ launch\ operation}} + \overbrace{c_{\mathrm{vOper_{prop}}}\left(\mathrm{n_{PAX}}\right)}^{\substack{per\ flight\ cost \\ propellant}} \\ &+ \underbrace{c_{Prod_{AF_{\#4}}}\left(n_{PAX},\ \mathrm{n_{AF}^{th}}\right) \cdot \left(\frac{1}{\mathrm{n_{LT_{AF}}}} + 5 \cdot 10^{-4}\right)}_{per\ flight\ cost\ of\ airframe} + \\ & \underbrace{c_{Prod_{RE_{\#4}}}\left(n_{PAX}, \mathrm{n_{RE}^{th}}\right) \cdot \left(\frac{1}{\mathrm{n_{LT_{RE}}}} + 5 \cdot 10^{-3}\right)}_{per\ flight\ cost\ of\ rocket\ engine} \end{aligned} \qquad (7)$$

$$c_{marginal} = \frac{c_{\mathrm{vOper_{tot}}}}{n_{PAX}} \qquad (8)$$

Using 200 flights as the lifetime of the airframe and 50 for the rocket engine, the total operational cost per participant (=$c_{marginal}$) as a function of the number of flights can be calculated (see Fig. 5). A new airframe or rocket engine is produced when the lifetime is reached, resulting in the discontinuities seen in the figure (the first, smaller one is caused by a new rocket engine at 50 flights, the larger drops are caused by the airframe at 200 flights). The steady decrease is due to the learning effect on launch operation costs.

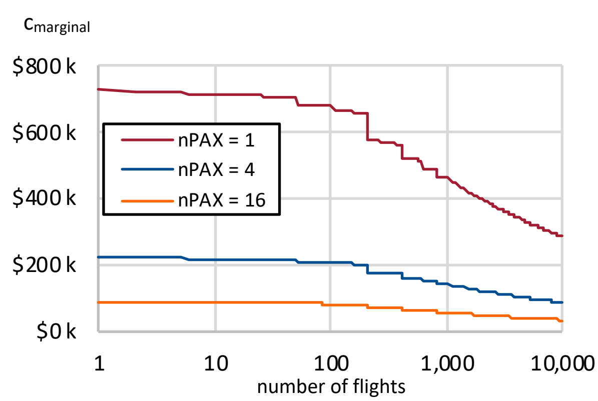

Fig. 5: Marginal cost (variable operational cost per participant) as a function of the number of flights for different vehicle sizes. Drops due to learning curve effects for the production of a new airframe or rocket engine. Lifetime of airframe and rocket engine is assumed to be 200 and 50 flights, respectively.

2.2.3 Fixed operating costs

We model the fixed costs by a one-time investment in infrastructure of 200 Million USD (Spaceport America costed $209M [11]). This investment is equally distributed over the 3 years before the operational period (or in other words over the last 3 years of development). Additionally, for every operational year $1.5M (around 5 WYr are assumed as fixed cost to keep the facilities and company infrastructure running.

2.2.4 Sales and Administration

Besides the cost development and fixed and variable operational costs, we account for the Sales and Administration cost, which can be estimated to be 15% of the revenue by analogy to similar companies [12].

2.3 Market model

2.3.1 Demand model

As shown in the introduction, the different demand forecasts vary highly between each other. Therefore, we do not aim to model the demand with great accuracy but aim for a transparent model with a clear identification of the uncertainty. We found that Kothari [13] did some relevant work basing his model on the Futron studies [1, 2]. Our model follows those two approaches. However, the data used by those sources on the wealth distribution are outdate. We therefore, update the model with current figures.

The goal of the demand model is to identify the size of the addressable market depending on the ticket price. We start with extracting data about the wealth distribution worldwide from the Credit Suisse "Global Wealth Databook 2017" [14] (see Table 4). As suborbital tourism is a luxury, only individuals above $1M of net worth (NW) are considered.

Table 4: Number of individuals by net worth worldwide in 2017 based on Credit Suisse "Global Wealth Databook 2017" [14]

minimum net worth	number of individuals
$1 million	31,365,072
$5 million	3,009,768
$10 million	1,527,597
$50 million	93,406
$100 million	49,088
$500 million	3,517
$1,000 million	2,232

The addressable market consists of individuals who are able to afford and willing to pay the ticket price (marked blue in Fig. 6). This subset depends on the ticket price and on the so-called *fraction of net worth spent on discretionary items (FoNW)* [13]. The FoNW is a critical factor in determining how much an individual is willing to spend on a once-in-a-lifetime adventure like a suborbital flight. A conservative baseline for the FoNW is 1.5% [13]. As discussed later, this will be our main source of uncertainty varying from 0.5% to 5% (as comparison, the first two space tourists, Tito and Shuttleworth, spent around 10% of their net worth, which we see as an extreme upper bound [13]). The required net worth is then calculated with the ticket price divided by the FoNW. With this information, the size of the number of individuals who are able to afford (red in Fig. 6) can be obtained from Table 4.

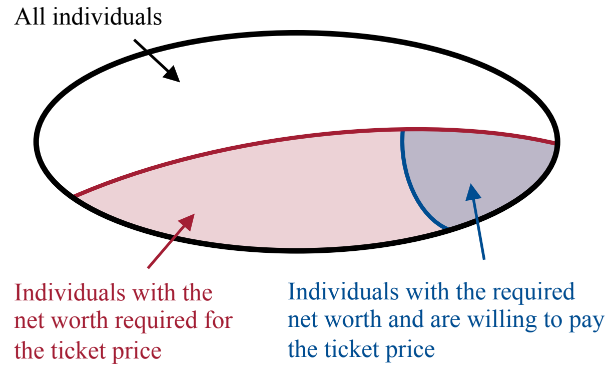

Fig. 6: Venn diagram of how the size of the market is determined. The black ellipse represents all individuals worldwide. The red area are the individuals who have the required net worth given the asked ticket price and the fraction of net worth spent on discretionary items (FoNW). The blue area is the subset of individuals who are able and willing to pay, which is the size of the addressable market.

Within the group of individuals who can afford the flight (red area), the willingness to actually spend the money depends on the ticket price as well. Table 5 shows this for ticket prices ranging from $25,000 to $500,000 based on the Futron market study [1, 2]. For ticket prices outside of this range, we have interpolated with a logarithmic function.

Table 5: Proportion of households which can afford are actually willing to buy [1]

Ticket price	Percentage of individuals willing to pay
$500,000	10%
$250,000	16%
$200,000	18%
$150,000	22%
$100,000	30%
$50,000	42%
$25,000	51%

After combining all of the information above and conduction a regression analysis, we obtain Eq. (9). With this relationship, we can calculate the number of individuals who are able and willing to pay as a function of the FoNW and the ticket price P_{ticket}. This demand curve determines the market size depending on the ticket price. Eq. (10) shows the same demand curve but rearranged as a function of the quantity (traditional micro-economical representation of a demand curve [15]). In Fig. 7, the demand curve for a FoNW of 1.5% is plotted.

$$n_{able+willing}(x_{FoNW}, P_{ticket}) = 1.75 \cdot 10^{18} \cdot x_{FoNW}^{1.42} \cdot P_{ticket}^{-1.98} \quad (9)$$

$$P_{ticket}(x_{FoNW}, n_{able+willing}) = n_{able+willing}^{-\frac{1}{1.98}} \cdot (1.75 \cdot 10^{18} \cdot x_{FoNW}^{1.42})^{\frac{1}{1.98}} \quad (10)$$

2.3.2 Pricing model

The pricing model determines the charged ticket price at the beginning of every year. This is modeled by decision rules based on pricing-theories from Microeconomics [15]. As stated in several sources [1, 2, 13], suborbital tourism is seen as a pioneering adventure, where individuals are willing to pay (WTP) more to be the first. We therefore have good reason to assume that we have sufficient market power to capture the consumer surplus by starting with higher prices and lower them as the market builds up, i.e. price discriminate the first customers. We implement this by dividing the pool of individuals into blocks starting with those who are willing to pay the most (see Fig. 7).

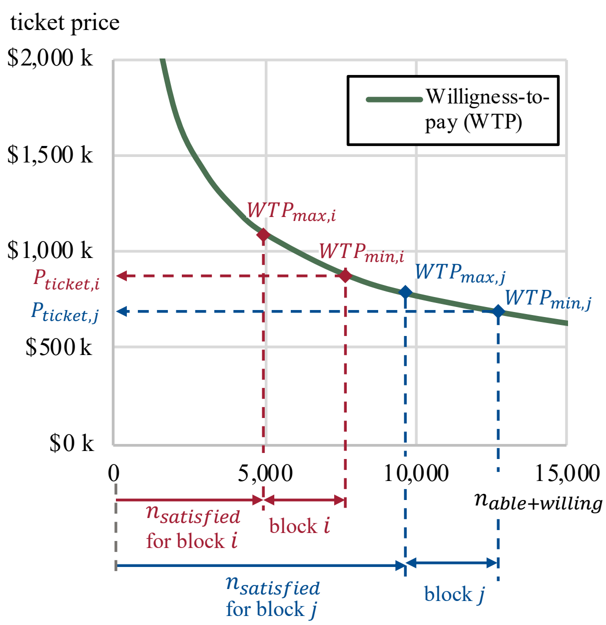

Fig. 7: Drawing of the implemented pricing strategy to extract the consumer surplus. Demand curve is given by Eq. (10) for a FoNW of 1.5%. First the individuals with the highest willingness-to-pay (WTP) are served (in drawing: Block i before Block j). The ticket price for each block is determined by the individual with the lowest WTP.

The size of this block is determined by the available capacity. The WTP of the individuals in this block depend on the number of people already flown (since the individuals with the highest WTP are served in the beginning, the WTP decreases with time). We update the size and WTP of the current block every year depending on the number of individuals flown. In our model, we charge one single ticket price for each block of individuals. This ticket price is determined by the individual with the lowest WTP within the block. To prevent unreasonably high prices in the beginning, an upper limit of $2 million per ticket is used, whereas the lower limit is set to the marginal cost (variable operational cost per participant (see Eq. (8)), as pricing below this point would result in losses.

In addition to extracting the consumer surplus, we implemented a ticket pre-sale. This has already been done: Virgin Galactic sold several hundreds of tickets by 2014 for $250,000 each [16]. In our model the company sells the tickets 5 years prior to the flight date with a 30 % discount (meaning the tickets cost 70% of the original price). This helps the company to generate revenues early-on to pay for the development costs. A study on the impact of the pre-sale has shown that it increases the NPV for every strategy and we therefore make this option part of our pricing strategy together with the price discrimination.

3. Strategy definitions

Besides the uncertainties, which the company cannot actively influence, there are strategies and decisions that the company needs to make. We focus here on two impactful decisions, from which we build five strategies that we compare in the result section.

Vehicle Size. As introduced earlier, the sizing of the vehicle is done with the number of participants n_{PAX}. We compare different strategies with vehicles having 1, 4, and 16 participants, referring to them later as small, medium, and large vehicles, respectively.

Fleet Expansion. If the demand exceeds the capacity, a decision needs to be made whether to increase the fleet and if so, by how much. We implement a decision rule at the end of each year that increases the fleet to meet all of the demand that is not met during the year. This increase in the fleet is limited by a number which we call *maximum fleet expansion per year* $n_{maxFleetExp}$. With this variable we can control how aggressive the company expanses its fleet. We consider three different expansion strategies: (1) passive expansion ($n_{maxFleetExp} = 1$), (2) neutral expansion ($n_{maxFleetExp} = 5$), and (3) aggressive expansion ($n_{maxFleetExp} = 10$).

Since there are three different vehicle size alternatives and three possible fleet expansion strategies, a full enumeration would lead to nine strategies. As a comparison of this number of strategies is impractical within the scope if this paper, we will focus on the most interesting strategies. We define a reference strategy and four strategies on the edges of the possible alternatives (see Table 6).

Table 6: Mapping between the active decisions to the strategies, which are compared in the result section.

$n_{maxFleetExp}$	n_{PAX} 1 (small)	4 (medium)	16 (large)
1 (passive)	Strategy A (passive expansion, small vehicle)		Strategy B (passive expansion, large vehicle)
5 (neutral)		Ref. strategy (neutral expansion, medium vehicle)	
10 (aggressive)	Strategy C (aggressive expansion, small vehicle)		Strategy D (aggressive expansion, large vehicle)

4. Results

In this section, we show two different results. First, we identify the three most impactful parameters by conducting a sensitivity analysis of the reference strategy (Section 4.1). In Section 4.2, we compare the distributions of the possible results of the five strategies.

4.1 Sensitivity analysis of the reference strategy

The goal of this analysis is to understand the impact of the uncertainty in the parameters. We identify the parameters with the biggest sensitivity and consider them in the Monte Carlo analysis in the following section.

Our model uses several parameters, which we need to estimate in order to calculate the NPV. Those 13 parameters are shown in Table 7. They can be grouped into three categories: business, operational, and cost. We estimate a default value, which can be seen as a best guess. Due to imperfect information, every parameter has an underlying uncertainty range. We define the range by a worst-case and best-case limit, where worst-case means that is has a negative impact on the NPV compared to the default value (and vice versa for best-case).

To understand the impact of the uncertainty on the NPV, we conduct a sensitivity analysis for every parameter for the reference strategy with a neutral expansion strategy and medium vehicle size. The results are compared in a Tornado diagram (see Fig. 8).

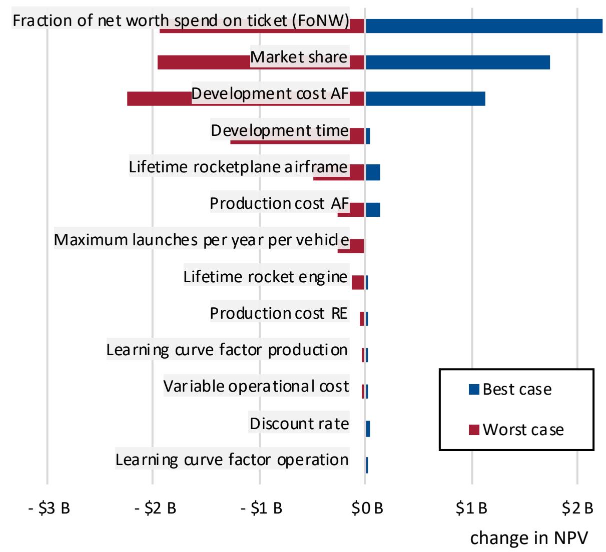

Fig. 8: Tornado diagram of the impact on the NPV of the parameters' uncertainty for the reference strategy with neutral expansion and medium vehicle. The biggest impact has the uncertainty around the FoNW, the market share, and the development cost of the airframe.

The parameters are ordered from highest to the lowest impact (sum of best and worst case). The reference

Table 7: Overview of the parameters and their uncertainty range

Parameter	**Symbol**	**Default value**	**Uncertainty range** Worst-case	Best-case
		Business		
Fraction of net worth spend on ticket (FoNW)	x_{FoNW}	1.5 %	0.5 %	5 %
Market share captured by our project	x_{MS}	50 %	10 %	90 %
Discount rate	d	15 %	20 %	10 %
		Operational		
Maximum launches per year per vehicle	$n_{max-launches}$	50	20	80
Development time	t_{dev}	5 years	7 years	3 years
		Cost		
Lifetime of rocket plane airframe	$n_{LT_{AF}}$	200 flights	50 flights	500 flights
Lifetime of rocket engine	$n_{LT_{RE}}$	50 flights	10 flights	200 flights
Learning curve factor for production	$f_{LC_{prod}}$	0.85	0.90	0.80
Learning curve factor for operation	$f_{LC_{oper}}$	0.95	1.00	0.90
Development costs airframe multiple	$c_{\text{Development}}$	1x	2x	0.5x
Production costs airframe multiple	$c_{Prod_{AF}}$	1x	2x	0.5x
Production costs rocket-engine multiple	$c_{Prod_{RE}}$	1x	2x	0.5x
Variable operational costs multiple	$c_{marginal}$	1x	2x	0.5x

vertical line is where the change in NPV is zero and it is obtained by setting all parameters to their default value. The blue bars indicate the increase in the NPV for the parameter's best case, and the red bar the decrease in the NPV for the worst case, respectively.

The analysis reveals four main insights:

First, the three most impactful parameters are the FoNW, the market share and the development cost of the airframe. These first two parameters describe the demand side, suggesting that developing a better understanding of the demand side should be a high priority. On the other side, investing e.g. in the improvement of the learning curve factor for operation will have little impact on the project's profitability.

Second, some parameters show a strong non-symmetric behavior, e.g. a reduction of the development time from 5 to 3 years (best case) shows only a marginal increase in the NPV. Whereas, an increase in the development time to 8 years results in -$1.7 billion lower NPV compared to the reference case. This result implies that accelerating the development to 3 years is not worth it, but it is important to ensure that it does not exceed 5 years. The reason for this is that the ticket pre-sale 5 years prior to launch significantly reduces the cashflow deficit (and makes it even positive for some demand scenarios). Therefore, the development costs (for up to 5 years) are not discounted to their fullest extend and have a reduced impact on the NPV. If the development time exceed the 5 years, then the pre-sale does not result in revenues for the first years and the development costs need to be discounted to its fullest extent. Similar arguments can be made about the other parameters which show a non-symmetric behavior (lifetime of airframe and rocket engine, maximum launches per year per vehicle, etc.).

Third, a different discount rate has very little influence on the NPV. This is a surprising result, since the discount rate has often a major impact on the NPV [5]. The explanation why the impact is very little, lies in our pricing strategy, specifically in the ticket pre-sale. By removing this option, we found that the discount rate influences the NPV by around $1 billion for the best case, and around -$ 0.5 billion for the worst case. Without the ticket pre-sale, the revenues are generated later and therefore must be discounted higher. This leads to a greater dependency on the discount rate.

Fourth, the choice of physical architecture has in view of the large uncertainties limited influence on the NPV. Compared to the impact of the uncertainties on the demand side, the impact of the cost side is significantly lower and only given by the development costs for the airframe. This development cost depends on the choice of the optimal architecture and therefore the impact of choosing a different architecture from the pareto front shown in reference [7] is limited.

Using the insight that the uncertainty for the FoNW, the market share and the development cost of the AF have the highest impact, we include them in the Monte Carlo simulation in the following section.

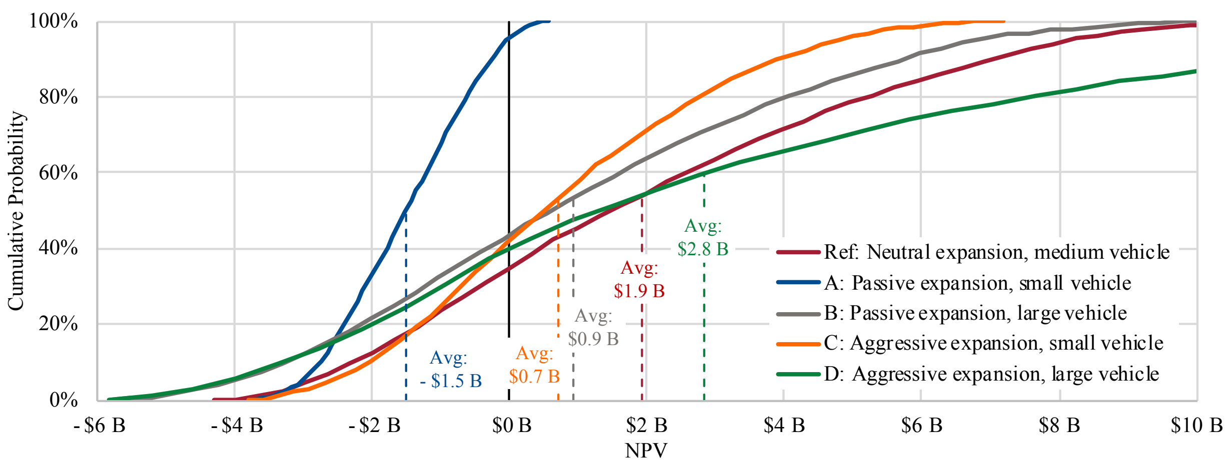

Fig. 9: Target curves for the five strategies. The vertical horizontal lines indicate the average NPVs.

Table 8: Summary of the important indicators sorted by the highest average NPV first

	Average expected NPV	Min NPV	Max NPV	Std. Deviation	Probability of incurring losses
D: Aggressive expansion, large vehicle	$2.8 B	- $5.6 B	$24.5 B	$5.8 B	41 %
Ref: Neutral expansion, medium vehicle	$2.0 B	- $4.4 B	$12.0 B	$3.4 B	33 %
B: Passive expansion, large vehicle	$0.9 B	- $5.9 B	$10.6 B	$3.3 B	42 %
C: Aggressive expansion, small vehicle	$0.7 B	- $3.9 B	$7.3 B	$2.3 B	43 %
A: Passive expansion, small vehicle	- $1.5 B	- $3.7 B	$0.5 B	$0.9 B	95 %

4.2 Distribution of possible results – target curves

To assess the financial profitability of the suborbital tourism industry, we use a discounted cash flow analysis (DCF). By combing the DCF with a Monte-Carlo simulation, a distribution of possible NPVs can be generated [5, 15]. The uncertainty distribution of the FoNW, the market share and the development cost of the AF is modelled uniformly between the worst case and best-case value as defined in Table 7. We use a sample size of 5,000 for each strategy to ensure that the cumulative distribution functions (CDFs) are converged.

This distribution of possible results is displayed in Fig. 9 with target curves, which show the cumulative probability of having NPVs smaller than the point of interest [17]. For example, the probability for a negative NPV for reference strategy (red line) is 33 % (and vice versa, it is positive with a probability of 67 %). The vertical dashed lines show the average NPV of the strategy. All values are in billion USD. As an additional view on the same results, important indicators are summarized in Table 8 ordered with the highest average NPV first.

We first compare the five strategies based on their average NPV. Four out of five strategies have a positive NPV (C, B, Ref, D) and only for strategy A - passive expansion with a small vehicle - the average NPV is negative with - $1.5 billion. The strategies B and C have a similar average NPV of just under $1 billion. Our reference strategy – neutral expansion, medium vehicle – has more than twice the NPV with $2 billion. The highest average NPV is reached by an aggressive expansion strategy in combination with a large, 16 participants, vehicle (Strategy D).

Next, we compare the distribution of results for the five strategies. The shape of the distribution can be seen graphically in Fig. 9, which is summarized by the statistical indicators in Table 8 (minimum/maximum NPV and the standard deviation). We observe that the standard deviation (and therefore the spread of the distribution) is higher for the strategies with a higher average NPV. This means, for example, for strategy D, that the average NPV is the highest but also the distribution is spread over a larger range of possible NPVs. In contrast, strategy A has a negative average NPV but the lowest spread in possible results and therefore is the most robust strategy (however it is only NPV positive with a probability of 5 %). Strategy B has the highest possible loss of - $5.9 billion, whereas strategy D has the highest possible gain of $24.5 billion.

5. Conclusion

We conclude that the suborbital tourism can probably be made commercially viable with four of the five strategies producing positive NPV on average. The main assumptions underlying these results are the development of a mass/safety optimized one stage single rocket engine vehicle, which was one of the simplest of the 33 architectures identified. In addition, we assumed the use of prepaid tickets (to reduce financing costs), zero development costs for engine, and a discount rate of 15%.

The main sources of uncertainties arise from the market factors (the fraction of net worth expended on the trip and market share captured), followed by the cost side factors (mainly the development cost of the airframe).

We found that the operational costs per participant without learning is significantly lower for a larger vehicle (around $700k for 1 participant, $200k for 4, and $90k for 16). The learning effect decreases those cost by half after around 3,500 flights.

The five strategy were framed with two decisions: one on the size of the vehicle (1, 4, or 16 participants) and one on the fleet expansion strategy (1, 5, or 10 newly produced vehicles per year called passive, neutral and aggressive, respectively).

From the Monte-Carlo simulation we conclude that strategy D (aggressive expansion with a large vehicle) and the reference strategy (neutral expansion with a medium vehicle) are the two dominant strategies a company can take given our model and uncertainty assumptions. Both dominant strategies have in-common a larger vehicle and a more aggressive expansion strategy compared to A, B, and C.

Which of these two strategies to choose, certainly depends on the risk tolerance of the company's management. Strategy D offers the better average NPV and a larger potential on the upside (above $7.5 billion NPV with a chance of 20%) but also a higher probability of having a negative NPV (41 %). Compared to this, the reference strategy has a lower average NPV and a lower upside potential (above $5 billion NPV with a chance of 20%) but a reduced downside risk: the probability of having a negative NPV is 33 %.

Appendix A (Variable operating costs)

Production costs

The productions costs are derived first as they are needed to calculate the amortization and maintenance costs. A surprisingly good rule of thumb is that the first unit costs (FUC) are 1/10 of the development costs. We will use this rule in the validation section to discuss the estimated costs of the CERs. However, we model the production costs more rigorously, by CERs and apply a learning curve to account for cost reduction for follow-on manufacturing units. We model this by a cost reduction factor f_{CR}, which is defined in Eq. (11). The default learning curve factor $f_{LC_{prod}}$ is assumed to be 85% for the production of the airframe and rocket engine. For the operational flight cost reduction $f_{LC_{oper}} = 0.95$ is used to account for the smaller marginal improvement over time.

$$f_{CR}(\mathrm{n}) = n^{\frac{\ln(f_{LC})}{\ln(2)}} \quad (11)$$

Similar to the development costs, the production costs can be broken down into those for engines and the airframe. The production cost of the airframe for our optimal architecture #4 is given in Eq. (12). This CER is derived by Koelle [8] from the winged orbital detailed concept studies FSSC-9/II and FSSC-1. The current production cost depends on the already manufactured units through the learning factor f_{CR}. The commercial factor and cost conversion value are equal to the ones defined in Eq. (5).

$$c_{Prod_{AF}}\left(\mathrm{m_{dry}}_{\mathrm{AF}}, \mathrm{n_{AF}^{th}}\right) = 5.83 \cdot m_{dry_{AF}}^{0.606} \cdot f_{CR_{AF}}(\mathrm{n_{AF}^{th}}) \cdot f_{C_{AF}} \cdot b \quad (12)$$
$$\text{for } m_{dry_{AF}} \in [10{,}000;\ 150{,}000]\ kg$$

with

$c_{Prod_{AF}}(\mathrm{m_{dry}}_{\mathrm{AF}}, \mathrm{n_{AF}^{th}})$:	Production cost for the n[th] rocket plane airframe in [$]
$c_{Prod_{AF\#4}}(n_{PAX}, \mathrm{n_{AF}^{th}})$:	Production cost for the n[th] architecture #4 rocket plane AF in [$]
$f_{CR}(\mathrm{n_{AF}^{th}})$:	Cost reduction factor for the n[th] airframe unit [-]

The production cost of the rocket engine depends on the type of engine (solid, liquid or hybrid). A complete list of how the production costs for all the different types are modelled by Frank [18] can be found in Guerster's Master's thesis [9]. Our optimal architecture has a liquid LH2/LOX rocket engine for which Koelle [8] developed the mass based CER shown in Eq. (13).We apply the same cost reduction factor as defined in Eq. (11). The commercial factor for rocket engines is assumed to be 0.2 based on [6, 8, 10].

$$c_{Prod_{RE}}\left(\mathrm{m_{dry}}_{\mathrm{RE}}, \mathrm{n_{RE}^{th}}\right) = 3.15 \cdot m_{dry_{RE}}^{0.535} \cdot f_{CR_{RE}}(\mathrm{n_{RE}^{th}}) \cdot f_{C_{RE}} \cdot b \quad (13)$$
$$\text{for } m_{dry_{RE}} \in [100;\ 3{,}000]\ kg$$

with

$c_{Prod_{RE}}(\mathrm{m_{dry}}_{\mathrm{RE}}, \mathrm{n_{RE}^{th}})$:	Production cost for the n[th] LH2/LOX rocket engine in [$]
$c_{Prod_{RE\#4}}(n_{PAX}, \mathrm{n_{RE}^{th}})$:	Production cost for the n[th] architecture #4 LH2/LOX rocket engine in [$]
$m_{dry_{RE}}$:	Dry mass of the rocket engine in [kg]
$f_{C_{RE}}$:	Commercial factor for rocket engines [-]; here 0.2

Variable operating costs

The operating costs per flight can be broken down on a high level into (1) launch operation, (2) maintenance, and (3) propellant [6, 8, 10]. For each of these components we develop a model as a function of the size of the vehicle.

Launch operation

The launch operation includes everything needed to support the launch process, such as pre-launch operation, transportation, insurance, employees for ground control, and pilots. The cost model is based on analogy with other vehicles. Table 9 gives an overview of typical operational costs for other airplanes and rocket planes. All costs were calculated in 2017 terms to allow comparison. Note, that we assume that one launch equals one flight hour and therefore the costs are comparable in the table.

The optimal architecture #4 is a suborbital supersonic rocket plane. We consider it to be closest to the X-15, but with current technology and a design with focus on reducing the variable costs. Given this focus, we think the operational costs can come down to the one of a SR-71 and will be $100,000/flight range for a four-participant vehicle. The resulting model of the launch operation cost is a function of the number of participants (= size of the vehicle). Eq. (14) shows the resulting relationship.

$$c_{vOper_{LO}}\left(\mathrm{n_{PAX}}, n_{flight}^{th}\right) = (\$80{,}000 + \mathrm{n_{PAX}} \cdot \$5{,}000) \cdot f_{CR_{Oper}}(n_{flight}^{th}) \quad (14)$$
$$\text{for } \mathrm{n_{PAX}} \in [1;\ 16]$$

Maintenance

The maintenance costs include cost for spare parts and manpower for inspection and component exchange. We model them for rocket engine and airframe as a function of the FUC. Based on Koelle [8], we account 0.5% per flight of the current production cost for maintenance for the rocket engine and 0.05% per flight for the airframe as shown in Eq. (15) and (16) (for comparison the values for the airframe of the SR-71 is 0.6% per flight and for the Concorde 0.008%). The

Table 9: Overview of operational costs for vehicles similar to a suborbital rocket plane

Vehicle	operational cost in 2017 terms	Source
Subsonic passenger airplane (average over narrow & wide bodies)	$3,000/h	[19]
Supersonic passenger airplane (Concorde)	$21,000/h	[20]
Supersonic military airplane (SR-71)	$65,000/h	[21]
Subsonic military heavy stealth bomber (B-2)	$144,000/h	[22]
Supersonic experimental rocket plane (X-15)	$4,500,000/flight	[23]

maintenance costs do not include amortization, for which we account in the next section.

$$c_{\mathrm{vOper}_{\mathrm{Maint}_{\mathrm{AF}}}}(\mathrm{n_{PAX}}, n_{AF}^{th}) = 5 \cdot 10^{-4} \cdot c_{Prod_{AF\#4}}(\mathrm{n_{PAX}},\ \mathrm{n_{AF}^{th}}) \quad \text{for } \mathrm{n_{PAX}} \in [1;\ 16] \tag{15}$$

$$c_{\mathrm{vOper}_{\mathrm{Maint}_{\mathrm{RE}}}}(\mathrm{n_{PAX}}, n_{RE}^{th}) = 5 \cdot 10^{-3} \cdot c_{Prod_{RE\#4}}(\mathrm{n_{PAX}},\ \mathrm{n_{RE}^{th}}) \quad \text{for } \mathrm{n_{PAX}} \in [1;\ 16] \tag{16}$$

Amortization

The amortization costs distribute the cost of producing the vehicle equally over each flight throughout the lifetime. The lifetime is modeled by a number of flights: $n_{LT_{AF}}$ for the airframe and $n_{LT_{RE}}$ for the rocket engine, respectively. The vehicle amortization cost is as the sum of both components as shown in Eq. (17).

$$c_{vOper_{Amor}}\left(\mathrm{n_{PAX}}, n_{AF}^{th}, n_{RE}^{th}, n_{LT_{AF}}, n_{LT_{RE}}\right) = \frac{c_{Prod_{AF\#4}}\left(n_{PAX}, \mathrm{n_{AF}^{th}}\right)}{n_{LT_{AF}}} + \frac{c_{Prod_{RE\#4}}\left(n_{PAX}, \mathrm{n_{RE}^{th}}\right)}{n_{LT_{RE}}} \quad \text{for } \mathrm{n_{PAX}} \in [1;\ 16] \tag{17}$$

Propellant

The rocket engine of our optimal architecture uses a LH2/LOX propellant combination. Koelle [8] gives mass based cost values of $c_{LOX} = \$0.21/kg$ for liquid oxygen and $c_{LH2} = \$7.16/kg$ for liquid hydrogen. With the mass model, the propellant costs can be estimated by using Eq. (18). With an oxidizes to fuel ratio of $x_{O-F} = 2.3$, and using the mass-based cost values, the right-hand side of the equation can be simplified as shown.

$$c_{\mathrm{vOper}_{\mathrm{prop}}}(\mathrm{n_{PAX}}) = (1497 + 147 \cdot \mathrm{n_{PAX}}) \underbrace{\left(\frac{c_{LH2}}{1+x_{O-F}} + \frac{c_{LOX}}{1+\frac{1}{x_{O-F}}}\right)}_{=\$2.32/kg} \quad \text{for } \mathrm{n_{PAX}} \in [1;\ 16] \tag{18}$$

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