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Selection of Geostationary Satellite Launch Vehicle Using Expected Value Analysis

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ABSTRACT

Selection of launch vehicle for a geostationary satellite is an important decision for satellite operators. Depending on only to the cost of the launcher may result unexpected consequences. Lifetime of the satellite is determined by the orbit parameters of the launcher. Success probability of the launcher can be deduced statistically by previous launches or using the insurance rate of the market for the selected launcher. Total cost of the satellite project includes insurance rate besides satellite and launcher costs. Design lifetime of a communication satellite is currently 15 years. Manufacturer warrants the operation of the satellite for 15 years via performance incentive or warranty payback mechanisms. But satellites continue to generate revenues during their maneuver lifetime which is more than 15 years. Expected value analysis is a powerful tool to include probabilistic nature of satellite projects. In this study a method proposed to select the best launcher for a given satellite program incuding satellite price, launch cost, insurance rate and lifetime parameters using expected value analysis.

Keywords: geostationary satellite, expected value analysis, launch vehicle selection

1. INTRODUCTION

Procurement of a communication Satellite consists of three main parts; satellite, launcher and insurance. The budget of a typical commercial satellite project varies around 250 MUSD depending on the size of the satellite [1]. Typical, launcher price starts from 62 MUSD baseline of SpaceX Falcon-9 to 109 MUSD of ULA Atlas-V rockets [1-3]. Launcher price may go higher if additional performance compare to baseline was required. Finally, insurance premium rates for launch plus one year in orbit have fallen down to 4 percent with the success of launchers during the last decade [4]. All these numbers are typical and may vary with commercial negotiations and time.

Analytic Hierarchy Process (AHP) was used for the selection of satellite manufacturer [5]. In a recent study, Data Envelopment Analysis (DEA) was utilized for the ranking of five possible launchers and compared to AHP and PROMETHEE [6]. Surprisingly, ranking of each method was different for the given case in the study. The main bottleneck of AHP and DEA is the subjective weight coefficients provided by the customer. Furthermore, it is difficult to compare importance of different metrics such as the launcher cost to the lifetime years of the satellite.

Launch vehicles have measurable statistics for their success rates. Space insurers calculate the risk of the launch using statistical methods, taking design and manufacturing related failures into account [7] and invest on their calculations.

Expected Value Analysis (EVA) is an easy to use and effective method for risk analysis [8]. While EVA was widely used in mine, petroleum investments, there are a few studies where EVA is

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utilized in human space flight insurance and economic feasibility of on-orbit satellite servicing [9-11].

2. EXPECTED VALUE ANALYSIS

Expected value of a satellite project can be defined as the difference between expected profit of sales and expected costs of satellite, launch and insurance. Expected value is calculated by summation of multiplications of monetary values and probabilities of events [12]. Expected value of the satellite project can be expressed as

$$E = \sum_i x_i \, P(x_i) \qquad (1)$$

where

x_i: Monetary value of event

$P(x_i)$: Probability of event i occurrence

Total cost of the satellite project is summation of satellite, launch vehicle and insurance costs. Insurance cost has to cover sum of satellite, launch vehicle and insurance premium. Income of the satellite project comes from capacity sales for TV broadcasting and data applications. We can assume an average yearly income during the lifetime of satellite. We will use the insurance premium rate for the probability of successful launch.

Design lifetime of commercial communication satellites is typically 15 years in current industry practice. Satellite manufacturers warrant the operation of satellite during design lifetime. There are warranty payback or performance incentive mechanisms to provide such warranties. But satellites continue to operate and provide services after the design lifetime. There will be some performance degradations and probability of failure occurrences will increase after the design lifetime. We will assume 50% decrease in incomes due to performance degradations or equivalently 0.5 probability of a failure that will cause complete loss of the satellite.

Service lifetime can be defined as duration between launch and disposal of the satellite. Service lifetime of the satellite depends of the performance of the launch vehicle and propellant budget and it is more than 15 years. Service lifetime is an important differentiator for launch vehicles together with insurance premium rate. Service lifetime of the satellite can be calculated using performance parameters of the launch vehicle and propellant budget of the satellite [13].

Using above explanations, expected value of a satellite project can be calculated as

$$E = Y.\left(15.Y + (T-15).\frac{Y}{2}\right).(1-P) - (S+L+I) \qquad (2)$$

where

E: expected value
Y: yearly income
T: lifetime
P: insurance premium rate
S: satellite cost
L: launch vehicle cost
I : Insurance cost

Satellite, launch vehicle and insurance costs are paid in advance of the launch. In case of successful launch with a probability of insurance premium rate, yearly income will be realized. If launch failure occurs, insurance company will pay back the cost of satellite, launch vehicle and insurance premium to the satellite operator.

3. COMPARISON OF LAUNCH VEHICLES

We will calculate the expected value for three different launch vehicles for an example. The satellite has 5050 kg total mass with 3000 kg of propellant and 2050 kg of dry mass. Launch vehicle user guides provide orbital parameters of geo-transfer orbit (GTO) or required delta-V to reach geosynchronous orbit (GSO) [14-23].

If required delta-V for GSO is not given, we have to calculate using orbital parameters of GTO. Semi-major of the GSO is 42164 km and the velocity at GSO is 3074.7 m/s [17, 18]. Velocity of the satellite on elliptic orbit is

$$V = \sqrt{GM\left(\frac{2}{R} - \frac{1}{a}\right)} \qquad (3)$$

where

GM: Earth Gravitational Constant (km^3/s^2)
R: Distance of the satellite to Earth center (km)
a: Semi-major axis of the GTO (km)

The required Delta-V for GSO can be calculated using cosine rule

$$\Delta V = \sqrt{V_a^2 + V_S^2 - 2V_aV_S\cos(i)} \qquad (4)$$

where

V_a : Velocity of the satellite at apogee (m/s)
V_s : Velocity of the satellite at GSO (m/s)
i: inclination between GTO and GSO orbits

Required ΔV for GSO is given Table 1.

Table 1: Required Delta-V (ΔV) for GSO.

Launch Vehicle	ΔV (m/s)
A	1495
B	1837
C	1019

Lifetime of the satellite for three launch vehicle options can be calculated using [13]. As we can see at Table 2 that lifetime of the satellite varies significantly for the selected launch vehicle.

Table 2: Lifetime of the satellite.

Launch Vehicle	Satellite Lifetime (years)
A	21.8
B	16.4
C	30.3

Insurance premium rate will add to the total cost besides satellite and launch vehicle. Premium rate will be used as the probability of a launch failure (see Table 3).

Table 3: Insurance premium rates.

Launch Vehicle	Premium Rate (%)
A	4
B	7
C	14

Expected values for each launch vehicle can be calculated using (2). It will be assumed that satellite costs are 100 MUSD, 60 MUSD and 120MUSD for launch vehicles respectively. Typical yearly income of 30 MUSD will be assumed for the example. Insurance premium will cover total of satellite, launch and insurance costs. Due to launch and insurance premium, total cost of the project has 74 MUSD difference between the minimum and maximum proposals. The cheapest proposal B has the worst lifetime as observed in Table 4. This type of dilemmas shows the need for a multi variable decision making method. Expected value analysis is one of these methods and easy to calculate, yet powerful.

Using (3) and (4) we have calculated required Delta-V for three launch vehicles. Delta-V of the launch vehicle C is already provided at user guide for the given satellite mass. Total cost of the project is presented in Table 4.

Table 4: Total cost of the project.

Launch Vehicle	Satellite (MUSD)	Launch (MUSD)	Insurance (MUSD)	Total (MUSD)
A	100	100	8	208
B	100	60	12	172
C	100	120	36	256

We can use (2) to calculate expected values of the satellite project for three different launch vehicles. While proposal B was providing the cheapest cost, now proposal C becomes the best choice with highest expected value due to lifetime (see Table 5).

Table 5: Expected values.

Launch Vehicle	Expected Value (MUSD)
A	322
B	266
C	329

In many satellite projects, new satellite replaces an existing one in the orbit. In such scenario, launch failure causes to loss of existing market due to three or more years of manufacturing time of a new satellite. Protection of orbital rights may require having a satellite before a certain time and launch failure may cause loss of orbital rights with huge amount of business loss. We can revise (2) for such additional loss scenarios

$$E_A = E - P.A \qquad (5)$$

where

E_A: expected value with additional cost
E: expected value without additional cost

P: insurance premium rate
A: additional cost due to a launch failure

For example, an additional 300 MUSD business loss will change the ranking of launch vehicles and proposal A will be the best choice (see Table 6).

Table 6: Expected values with additional cost.

Launch Vehicle	Expected Value (MUSD)
A	310
B	245
C	287

4. DISCUSSION AND CONCLUSION

Launch vehicle selection is an important decision for a commercial satellite project. Cost of the launch vehicle, insurance premium rate, lifetime of the satellite and additional costs due to launch failure has to be taken into account for decision. Expected value analysis is a well-known tool for investment decisions, easy to use and powerful. In this study, expected value analysis has been adapted for launch vehicle selection.

Lifetime of the satellite which is determined by the selected launch vehicle performance, becomes dominating parameter if there are not additional business losses expected due to a launch failure. In such cases, low premium rate will point the best launch vehicle. These results are meaningful as expected in real satellite operation scenarios and encourage using expected value analysis in selection of launch vehicles at satellite projects.

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