Aggregated Preference Value Analysis of Small Satellite Launch Opportunities*

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Due to the lack of matched dedicated small satellite launch vehicles, launch opportunities as a rideshare or piggyback using a highly reliable launch system has become increasingly important for small satellite developers. The objective of this paper is to provide an aggregated value method as a strategy for developers to evaluate launch opportunities, as well as an approach for the launchers to capture the market dynamics. Based on an up-to-date launch record, a reliable launch database for multi-attribute evaluation is established. Efforts are made to quantify the abstract and concrete attributes of launch systems. An aggregated preference value model is developed, translating different inherited capabilities of launch systems into integrated preference value as a reference for decision-making. The preference values of the launch opportunities of different launch vehicles are explored in a case study by the method proposed, and its feasibility and applicability for small satellite launch system evaluation tasks is validated.

Key Words: Small Satellite, Preference Function, Launch Opportunity, Decision Making

1. Introduction

In recent years, small satellites have been playing an increasingly more significant role in space activities as the result of growing government interests, industry initiatives and technological advancements (Fig. 1).^{1,2)} However, the miniaturization of satellites has not been fully followed in parallel with the reduction in payload capacity of our launch vehicles, or in other words, the development of dedicated small satellite launch vehicles.³⁾ On one hand, the motivation of lower cost and risks has stimulated an upward demand and interest in developing dedicated launch vehicles: at least 20 were in development by the year 2015.^{3–5)} On the other hand, the current market still shows an intention to use conventional launch vehicles, where more satellites are being integrated on larger vehicles. One recent case is that India has set a record by successfully launching 104 satellites in a single trial on 15 February 2017.⁶⁾ Under these circumstances, before dedicated vehicles reach their technical maturity, small satellite developers need to seek rideshare or piggyback opportunities as secondary payloads. Thus, no matter how quickly the market trend changes, the success of small satellite projects largely depends on the performance of launch systems and the acquisition of launch opportunities.

As the launch market continues to heat up, some launch vehicles become less desirable in the competition while others become extremely popular. Although there are still doubts on whether this market trend represents the actual de-

mand from both technical and economical perspectives, analysis of known launch histories is necessary to uncover current key concerns from different aspects.

From the demand side, optimized decisions are required for practical considerations, including customer affordability, system reliability, technology maturity and the availability of launch opportunities. From the provider side, such intentions are crucial references for launch vehicles to adapt to the dynamic trend in the emergence of market imbalance.

In order to provide a more comprehensive strategy for satellite developers to make decisions and benefit the providers by enabling them to understand market trends, an aggregated preference value method for the overall capability evaluation of small satellite launch opportunities is proposed in this paper. Based on historical launch records, efforts have been made to update a launch vehicle database established in our previous research, which serves as the performance database for multi-attribute decision-making. A Bayesian analysis of the future success rate of current active launch vehicles is performed to estimate their predicted reliability. The concept of availability of launch opportunities is established and quantified. Focusing on multiple concerns towards the capabilities of launch vehicles, an aggregated preference value model is developed, allowing for a comprehensive decision-making process that integrates developers' experiences and technical indicators. The preference values of the launch opportunities of currently active launch vehicles are explored in a case study using the method proposed. The results validate that this analysis is capable of small satellite launch system evaluation and supports the decision-making process.

2. Launch Capability Analysis

2.1. Updated launch vehicle database

The launch vehicle database established in our previous research is updated with the launch data from the International Reference Guide to Space Launch Systems,⁸⁾ Space Mission Engineering: The New SMAD,⁹⁾ and online space launch system data.^{10–12)} Note that although the cost per kilogram actually delivered to orbit may be different from that advertised due to the amount of wasted payload capacity every launch,¹³⁾ we still use the total cost divided by the maximum payload as the metric for unit cost. Based on the previous version,¹⁴⁾ one new attribute, namely average launch cycle, is added to the database to reveal the general frequency of the launch activities. Note that all of the launch systems presented here are classified into two categories following the classification in The New SMAD according to their payload capability to LEO; namely, small launch systems (<5,000 lb) and medium and intermediate launch systems (<12,000 lb and <25,000 lb, respectively). By 31

January 2017, different fundamental concerns of the selected launch systems are exhibited in Table 1 and Table 2, to cover the most significant performance indices of launch systems.

Please notice that all of the heavy launchers (e.g., LEO payload capability >25,000 lb) are excluded in the proceeding analysis. This kind of launch systems is mainly designed for heavy transportation missions such as cargo delivery to the International Space Station (ISS) or deep-space exploration tasks. Generally, heavy launch vehicles are less appealing for launching small satellites as compared to dedicated vehicles, although they are capable. Currently, heavy launch vehicles are still not one of the mainstream means for launching small satellites into LEO due to the demand (i.e., small market size). Therefore, despite some well-known heavy launch systems that have executed small satellite missions, only small, medium and intermediate launch systems are fully discussed in this study.

2.2. Availability analysis

2.2.1. Availability expectation analysis

In the reliability theory, availability is typically measured as a factor of reliability. When considering the case of launch opportunities, availability is apt to be a factor independent of reliability. The formal definition and main extended meaning of availability—the quality of being able to be used or obtained and the state of being otherwise unoccupied¹⁵⁾—indicate that this word defines a free and accessible approach to some subject. There are many ways of quantifying this attribute. For example, as is described in the definition of “achieved availability A,” it is calculated by the mean time between maintenance (MTBM) action, and the mean maintenance time (MMT).¹⁶⁾

$$A = \frac{\text{MTBM}}{\text{MTBM} + \text{MMT}} \quad (1)$$

Fig. 1. Small satellite launch activity history recorded in the UCS satellite database.⁷⁾

Table 1. Small launch systems (small launch vehicles are identified by their payload capabilities in pounds to LEO (<5,000)).

Vehicle	Country	Unit cost (FY2010\$/kg)		Total launches	Success rate (%)	Average launch cycle (d)	Last launch date (DDMMYYYY)	Status
		LEO	SSO					
Athena 2	USA	15.8	28.1	3	66.67	313	24/09/1999	Retired
Delta 2000s	USA	31.1	41.5	44	97.73	66	06/10/1981	Retired
Epsilon	Japan	31.7	84.4	2	100.00	1193	20/12/2016	Active
Falcon 1	USA	10.4	17.0	5	40.00	302	14/07/2009	Retired
Kosmos 3M	Russia	12.1	23.7	446	95.07	35	27/04/2010	Active
KZ	China	8.7	/	3	100.00	601	09/01/2017	Active
Minotaur I	USA	35.9	68.7	11	100.00	505	20/11/2013	Active
Minotaur IV	USA	13.3	22.0	5	100.00	131	27/09/2011	Active
M-V	Japan	37.7	74.6	7	85.71	403	22/09/2006	Retired
Pegasus	USA	43.1	100.4	43	87.88	256	15/12/2016	Active
Rockot	Russia	9.5	18.5	30	90.00	322	04/06/2016	Active
Shavit 1	Israel	58.5	/	6	66.67	1127	06/09/2004	Active
Shtil'	Russia	15.7	/	2	100.00	2880	26/05/2006	Active
START	Russia	19.5	73.6	6	100.00	956	25/04/2006	Active
Strela	Russia	9.2	20.5	3	100.00	2016	19/12/2014	Active
Taurus	USA	18.8	35.9	9	66.67	771	04/03/2011	Active
Taurus XL	USA	28.5	52.6	3	33.33	1270	04/05/2011	Active
Titan 2	USA	25.2	43.5	13	92.31	460	18/10/2003	Retired
Vega	Italy	17.8	25.1	8	100.00	251	05/12/2016	Active
Volna	Russia	11.2	39.3	5	40.00	944	06/10/2005	Active

Table 2. Medium and intermediate launch systems (medium and intermediate launch vehicles are identified by their payload capabilities in pounds to LEO (<12,000 and <25,000, respectively)).

Vehicle	Country	Unit cost (FY2010\$/kg)		Total launches	Success rate (%)	Average launch cycle (d)	Last launch date (DDMMYYYY)	Status
		LEO	SSO					
Ariane 44L	Europe	15.0	23.6	40	97.50	128	15/02/2003	Retired
Atlas 2AS	USA	15.4	25.6	30	100.00	135	31/08/2004	Retired
Atlas 3	USA	13.2	/	6	100.00	343	03/02/2005	Retired
Cyclone 2	Ukraine	8.4	/	106	99.06	128	24/06/2006	Retired
Cyclone 3	Ukraine	6.9	/	122	93.44	95	30/01/2009	Retired
Delta 2	USA	14.6	24.0	114	98.25	73	28/10/2011	Active
Delta 2M	USA	19.3	30.8	23	100.00	194	31/01/2015	Active
Delta 4M	USA	9.7	13.4	3	100.00	667	04/11/2006	Active
Dnepr	Russia	4.6	8.9	22	95.45	277	25/03/2015	Active
Falcon 9 V1.0	USA	5.4	/	5	80.00	250	01/03/2013	Retired
GSLV	India	8.8	/	10	50.00	625	08/09/2016	Active
Long March 2C	China	9.5	15.3	41	97.56	294	14/11/2014	Active
Long March 2D	China	5.9	15.8	31	100.00	297	21/12/2016	Active
Long March 3A	China	9.8	11.8	25	100.00	337	29/03/2016	Active
Long March 3C	China	11.3	15.8	15	100.00	224	22/11/2016	Active
PSLV-G	India	5.4	19.2	12	83.33	764	26/09/2016	Active
PSLV-CA	India	7.2	18.3	11	100.00	316	16/12/2015	Active
PSLV-XL	India	5.3	11.5	13	100.00	212	07/12/2016	Active
Soyuz	Russia	7.4	/	32	93.75	116	14/10/1976	Retired
Soyuz 2	Russia	6.9	11.3	63	92.06	72	28/01/2017	Active
Soyuz U	Russia	7.8	12.7	785	97.32	20	01/12/2016	Active

If this definition is followed in the case of measuring the availability of launch opportunities, it would show a correspondence that MTBM is equal to the time spent on the launch activity, including its preparation time, and MMT is equal to the time gap between every two launches. Therefore, the availability of a launch system can be written as

$$A = \frac{\text{MTBM}}{\text{average cycle}} \quad (2)$$

where, MTBM denotes the time spent for one launch activity and average cycle is the average time gap between two launches including MTBM for a launch system. Please notice that we do not consider the condition of the maintenance of an individual launch vehicle in conflict with a particular launch window. In other words, Eq. (2) is valid for a series, or family, of such launchers during the service period. Here, we use the sample mean $\bar{x}$ to substitute the average cycle. Note that MTBM is a measurement that varies for different space missions. Thus, the factor, sample mean launch cycle $\bar{x}$, is preferred to indicate the level of availability in this case. That is, for the same MTBM, the shorter the $\bar{x}$, the more frequent the launch system is in action and the greater the availability of the launch opportunity.

2.2.2. Confidence intervals analysis

As an unbiased estimator of the true mean of the launch cycle, $\bar{x}$ is able to reflect the regular patterns of launch activities as well as the average level of the availability of the launch system. However, this significant statistic parameter fails to illustrate the fluctuation in launch activities. Therefore, in order to supplement the explanation of launch availability, we further derive the confidence interval of the average launch cycle based on the analysis of the launch activity history of space launch systems.

To begin with, a comparison of sample mean of the launch

Fig. 2. Total launch times vs. average launch cycle for small launch vehicles.

Fig. 3. Total launch times vs. average launch cycle for medium-sized launch vehicles.

cycle and total launch times of different launch systems is presented in Fig. 2 and Fig. 3, with colors differentiating the retired and active systems. As is shown in the graphs, compared with their larger competitors, most of the small launch vehicles have a comparatively longer launch cycle and fewer historical launches. One trend shared by both figures is that, generally, the one with a shorter cycle has more

Fig. 4. Box plots show median values (solid horizontal line), lower and upper quartiles (Q_1 and Q_3 at box outlines), lower and upper fences (quartiles $\pm 1.5IQR$, whiskers, where $IQR = Q_3 - Q_1$), mild outliers and extreme outliers (red plus outside and inside red dashed boxes) and abnormal data rate indicated by red percentages.

Fig. 5. Launch cycle vs. SSD with regression line by OLS (selected launch systems).

launches (e.g., points located in the right bottom), which denotes a higher level of technical maturity.

For further analysis, we select 13 launch systems from both categories to study the statistical facts in the launch activity record. All of the representatives should have a number of launch records over 20 to be considered a reliable data source. From examination of the fence points and data, each group has points exceeding the upper fence with an abnormal data rate ranging from 5.7% to 13.1%, where the abnormal data rate is equal to the percentage of outliers in the entire sample (see the red tags in Fig. 4). These extreme outliers ($>$ quartiles $+ 3IQR$) marked with red dashed boxes in Fig. 4 are removed, while mild outliers are kept as a caution. Then, in the scatter plot of the trimmed data, shown in Fig. 5, a positive correlation can be observed with respect to the average value of the launch cycles $\bar{x}$ and the corrected sample standard deviation s . Therefore, a linear regression function using the ordinary least squares (OLS) method is applied

$$s = 0.94608\bar{x} - 3.0647, \quad R^2 = 0.9717 \quad (3)$$

where, R^2 is the coefficient of determination.

In order to check whether or not the regression model proposed fits the data well, a F -test is conducted applying a significant level $\alpha = 0.01$ to test the null hypothesis for lack of linear fit. Since the F statistic, in this case equaling 377.9223, is greater than the critical F value $F_{1-\alpha}(1, n-2) =$

$F_{0.99}(1, 11) = 9.65$, the null hypothesis could be rejected; meaning that the linear model proposed fits well.

To further decide the confidence interval for the estimate of the true mean μ , especially the upper limit of the mean representing the longest possible launch cycle, a one-sided test for true mean is adopted. Since the standard deviation σ is unknown for the small size samples, Student's t -distribution is used as the critical value. Suppose that the test statistic $T = (\bar{x} - \mu)/(s/\sqrt{n})$ is distributed as a Student's t -distribution with $n - 1$ deg of freedom, there is a probability $1 - \alpha$ that T could be less than $t_{1-\alpha}(n - 1)$

$$\begin{aligned} Pr(T < t_{1-\alpha}(n - 1)) &= Pr\left(\frac{\bar{x} - \mu}{s/\sqrt{n}} < t_{1-\alpha}(n - 1)\right) \\ &= (1 - \alpha) \times 100\% \end{aligned} \quad (4)$$

where, n is the sample size, and s is the sample standard deviation yield to the regression function (Eq. (3)) for those launch systems with limited launch attempts. Then, the upper confidence limit (UCL) of the mean with a confidence level $(1 - \alpha)$ can be calculated using the following equation:

$$UCL_{1-\alpha} = \bar{x} + t_{1-\alpha}(n - 1) \frac{s}{\sqrt{n}} \quad (5)$$

The resulting UCL denotes the greatest average value that will occur for a given confidence level and population size. As for the variable launch cycle, this introduces an upper bound that the possible average launch cycle could be shorter than with the possibility of $1 - \alpha$.

Therefore, with the average launch cycle $\bar{x}$ and sample standard s as the inputs, the upper confidence limit (UCL) of the mean of launch cycle of each launch system can be obtained (shown in Table 3) taking α as 0.05. The higher the rank, the less maximum potential waiting time for a launch opportunity. From Table 3, we also find that, although in general, launch systems whose average launch cycles are shorter usually have a shorter UCL of mean as well; however, from a local comparison, those with a shorter $\bar{x}$ do not always rank high (e.g., KT-1). As a result, the UCL of the mean for a launch cycle could serve as a supplementary judgment index of launch availability to help with decision-

Table 3. Ranking of the $UCL_{0.95}$ of the mean of small launch systems, and medium and intermediate launch systems. (The average launch cycles of 13 selected launch vehicles (shown in Fig. 5) are calculated from data sorted by deleting the extreme outliers, which in this table results in different values from those in Table 1 and Table 2.)

No.	Small launch system	$UCL_{0.95}$ (d)	Average launch cycle (d)	No.	Medium and intermediate launch systems	$UCL_{0.95}$ (d)	Average launch cycle (d)
1	Kosmos 3M	40	35	1	Soyuz U	14	13
2	Delta 2000-Series	81	66	2	Soyuz 2	43	35
3	Minotaur IV	273	131	3	Delta 2	54	49
4	Pegasus	316	231	4	Cyclone 3	65	57
5	Vega	423	251	5	Cyclone 2	111	96
6	Rockot	444	322	6	Ariane 44L	145	121
7	Falcon 1	635	302	7	Soyuz	153	116
8	Titan 2	684	460	8	Atlas 2AS	169	135
9	M-V	714	403	9	Delta 2M	248	194
10	Minotaur I	780	505	10	Long March 2D	280	211
11	KT-1	858	333	11	Long March 2C	282	228
12	Taurus	1258	771	12	PSLV-XL	305	212
13	Athena 2	1619	313	13	Long March 3C	323	224
14	START	1815	956	14	Atlas 3	343	343
15	Athena 1	1931	746	15	Dnepr	374	277
16	Volna	1991	944	16	Long March 3A	447	337
17	Shavit 1	2215	1166	17	PSLV-CA	488	316
18	Shavit 2	2920	1127	18	Falcon 9 V1.0	525	250
19	KZ	3126	601	19	GSLV	990	625
20	Naro-1	3262	627	20	PSLV-G	1157	764
21	Taurus XL	6621	1270	21	Delta 4M	3471	667
22	Strela	10518	2016				

making when there are various options yet the performance levels are very close to each other.

2.3. Reliability analysis

The possibility of the future success for the next launch is of great importance in performance assessment. Let s denote the number of successful launches observed in a random launch record of t attempts. Assume that we know nothing before the launch of a given vehicle, thus the proportion p of successful launches is uniformly distributed over the interval $(0, 1)$,¹⁷⁾

$$g(p) = \begin{cases} 1 & 0 \leq p \leq 1 \\ 0 & \text{elsewhere} \end{cases} \quad (6)$$

where, the probability density function $g(p)$ is a prior distribution. For a given p , s will have a binomial distribution given by

$$f(s|p) = \binom{t}{s} p^s (1-p)^{t-s} \quad s = 0, 1, \dots, t \quad (7)$$

Then, we can have the density function of the distribution for the future fraction of successful launches

$$\begin{aligned} f(p|s) &= \frac{f(s|p)g(p)}{\int_0^1 f(s|p')g(p')dp'} \\ &= \frac{\Gamma(s+1)\Gamma(t-s+1)}{\Gamma(t+2)} p^s (1-p)^{t-s} \\ & \quad 0 \leq p \leq 1 \end{aligned} \quad (8)$$

which is the beta density function: beta $(s+1, t-s+1)$.

Thus, the Bayes estimate of p is the mean of this posterior density function; namely,

$$\int_0^1 p' f(p'|s) dp' = \frac{s+1}{t+2} \quad (9)$$

According to the study by Howard,¹⁸⁾ the best estimate of probability of success in the next launch for a given launch vehicle is the mean of the posterior distribution for future frequency of launch success. Therefore, the predicted reliability of active representative launch vehicles can be calculated using Eq. (9). The results are illustrated in Table 4. Figures 6 and 7 also demonstrate the results with the total launch times and colors representing the average launch cycle of each launch vehicle. Note that some points coinciding with others for closing value can still be differentiated by their performance in average launch cycle (e.g., cycle_(Kuaizhou) = 601 d, cycle_(Strela) = 2,016 d, cycle_(Epsilon) = 1,193 d and cycle_(Shtil') = 2,880 d).

Compared to the small launch vehicles shown in Fig. 6, the medium and intermediate launch vehicles in Fig. 7 have better performance in reliability, experience and availability with higher predicted reliability, more total launch times, and shorter average launch cycles, which can also be found in Table 4. Moreover, points with a warm color in Fig. 7 tend to converge in the upper part of the graph (i.e., predicted reliability $\geq 90\%$), with more launches than green points. This indicates a close relationship between abundant experience, higher availability and better reliability. As for small launch vehicles, there is no such obvious trend shown in the graph. However, when only considering those with more than 10 launches, a similar conclusion will be obtained that more launch experience realizes progress in technique maturity, especially in terms of predicted reliability.

Note that the predicted reliability of some launch vehicles may differ significantly from the success rate achieved (e.g.,

Table 4. Comparison between success rate and predicted reliability.

Launch vehicle	Launch success/Total launches	Success rate (%)	(Predicted reliability, standard deviation) (%)
Small			
Epsilon	2/2	100.00	(75.00, 19.36)
Kosmos 3M	424/426	95.07	(94.87, 1.04)
KT-1	2/4	50.00	(50.00, 18.90)
Kuaizhou/KZ	3/3	100.00	(80.00, 16.33)
Long March 11	1/1	100.00	(66.67, 23.57)
Long March 6	1/1	100.00	(66.67, 23.57)
Minotaur I	11/11	100.00	(92.31, 7.12)
Minotaur IV	5/5	100.00	(85.71, 12.37)
Pegasus XL	29/33	87.88	(85.71, 5.83)
Pegasus	38/43	88.37	(86.67, 5.01)
Rockot	27/30	90.00	(87.50, 5.76)
Shavit 1	4/6	66.67	(62.50, 16.14)
Shavit 2	4/4	100.00	(83.33, 14.09)
Shtil 1	2/2	100.00	(75.00, 19.36)
START	6/6	100.00	(87.50, 11.02)
Strela	3/3	100.00	(80.00, 16.33)
Taurus XL	1/3	33.33	(40.00, 20.00)
Taurus	6/9	66.67	(63.64, 13.89)
Vega	8/8	100.00	(90.00, 9.05)
Volna	2/5	40.00	(42.86, 17.50)
Medium			
Delta 2	112/114	98.39	(97.41, 1.43)
Delta 2M	33/33	100.00	(97.14, 2.78)
Delta 4M	3/3	100.00	(80.00, 16.33)
Dnepr	21/22	95.45	(91.67, 5.53)
GSLV	5/10	50.00	(50.00, 13.87)
Long March 2C	40/41	97.56	(95.35, 3.17)
Long March 2D	31/31	100.00	(96.97, 2.94)
Long March 3A	25/25	100.00	(96.30, 3.57)
Long March 3C	15/15	100.00	(94.12, 5.55)
Long March 4C	19/20	95.00	(90.91, 5.99)
PSLV-CA	11/11	100.00	(92.31, 7.12)
PSLV-G	10/12	83.33	(78.57, 10.59)
PSLV-XL	15/15	100.00	(94.12, 5.55)
Soyuz 2	58/63	91.94	(90.77, 3.58)
Soyuz U	764/785	97.32	(97.20, 0.59)

Long March 11, Long March 6 and Taurus XL). This is due to prior knowledge and lack of launch data. With the accumulation of launch experience, the impact from prior knowledge is reduced while the number of launches has a greater impact, thereby reducing the difference between predicted reliability and current success rate. To accurately evaluate launch systems with limited launch data, efforts could be made to find other prior distributions to make full use of all available information.

3. Aggregated Preferences Value Analysis

Although the updated launch vehicle database provides practical indices to evaluate launch opportunities, it is less straightforward in providing reliable views standing for all concerned attributes by a series of values rather than a standard unit. A more intuitive and understandable method to evaluate the comprehensive capabilities of various launch systems is developed using decision-maker (DM) preferences. In this part, the preference types of different attributes are first introduced. Then, the translation procedure is imple-

Fig. 6. Scatter plot of predicted reliability of small launch vehicles.

Fig. 7. Scatter plot of predicted reliability of medium launch vehicles.

mented to transform essential knowledge and concerns from the DM preferences into separate quantified ranges. Finally, an aggregated preferences value function is established to integrate all of the attributes into a single metric. With the aggregated preferences value, the promising launch opportunity can be selected while taking designed objectives into account.

3.1. Classifications of objectives

As is described in the theory of physical programming,¹⁹⁾ the types of different criteria depend on the sharpness of the preference. In this study, there are two types of preferences: 1) Type-1: smaller is better and 2) Type-2: larger is better. For criterion i , there are N ranges to differentiate the levels of desirability towards all of the M criteria. The physical values of the criterion i at the boundaries of the ranges f_i^k ($i = 1, \dots, M; k = 0, 1, \dots, N$) are used to quantify the preferences in an ascending order, with the highest preference value for the first and lowest for the last. In an actual case, these standards are set mostly by the experience and knowledge of the experts. An example of designed desirability ($N = 5$) is shown in Table 5.

3.2. Aggregated preference function

The mathematic formulation of the preference function is established in order to quantify the different criteria in a relatively fair way. Aiming at this goal, the same set of images α_k is implemented for preference function construction in each value range respectively with a piecewise exponential function.²⁰⁾ Those α_k at boundaries f_i^k can be expressed as

$$\alpha_k = \begin{cases} 0, & k = 0 \\ M^{k-1} \cdot \alpha_{ini}, & 1 \leq k \leq N \end{cases} \quad (10)$$

Table 5. Preference order and their attribution of Type-1 and Type-2.

Level	Description	Type-1	Type-2
A	Highly desirable	$f_i^0 < f_i \leq f_i^1$	$f_i^1 \leq f_i < f_i^0$
B	Desirable	$f_i^1 < f_i \leq f_i^2$	$f_i^2 \leq f_i < f_i^1$
C	Tolerable	$f_i^2 < f_i \leq f_i^3$	$f_i^3 \leq f_i < f_i^2$
D	Undesirable	$f_i^3 < f_i \leq f_i^4$	$f_i^4 \leq f_i < f_i^3$
E	Highly undesirable	$f_i^4 < f_i \leq f_i^5$	$f_i^5 \leq f_i < f_i^4$

Fig. 8. Preference function Type-1 with $N = 5$.¹⁴⁾

where α_{ini} is a constant that is used to compare the relative preferences of different systems. Thus, image α_{ini} can be chosen randomly from any small value as its absolute value does not make a difference. Here $\alpha_{ini} = 0.02$ for the rest of this paper.

(1) Type-1: the smaller the better

Without loss of generality, we define the preference function with n order in the range k (e.g. $f_i^{k-1} < f_i(x) \leq f_i^k$) as

$$p_k(x) = \alpha_{k-1} + \beta_k \left| 1 - e^{-n \left(\frac{f_i(x) - f_i^{k-1}}{f_i^k - f_i^{k-1}} \right)} \right| \quad (11)$$

For the following examples, n is set to be -2 . Since $p_k(f_i^k) = \alpha_k$, the parameter β_k can be obtained.

$$\beta_k = \frac{\alpha_k - \alpha_{k-1}}{|1 - e^{-n}|} \quad (12)$$

As a result, for criterion i , the Type-1 preference function can be expressed as

$$n_i^1(x) = \begin{cases} 0, & f_i(x) < f_i^0 \\ p_k(x), & f_i^{k-1} \leq f_i(x) \leq f_i^k \\ p_N(x), & f_i(x) > f_i^N \end{cases} \quad (13)$$

with $1 \leq k \leq N$ and $p_N(x) = \alpha_N$.

(2) Type-2: the larger the better

Similarly, the preference function for criterion i of type-2 can be defined as

$$n_i^2(x) = \begin{cases} 0, & f_i(x) > f_i^0 \\ p_k(x), & f_i^k \leq f_i(x) \leq f_i^{k-1} \\ p_N(x), & f_i(x) < f_i^N \end{cases} \quad (14)$$

Examples of these two type preference functions are given in Figs. 8 and 9.

As soon as the preference function in each value range is defined, we use an aggregated preference function $V(x)$ to integrate the preference value of all the criteria.

Fig. 9. Preference function Type-2 with $N = 5$.¹⁴⁾

Table 6. Preferences of four criteria for launch vehicles.

Criterion	Type	f_i^0	f_i^1	f_i^2	f_i^3	f_i^4	f_i^5
Unit cost (FY2010\$/kg)	1	1	15	25	35	50	500
Predicted reliability (%)	2	100	95	90	80	70	0
Total launches	2	1000	101	51	21	5	0
Availability	2	1	1/3	1/9	1/18	1/36	1/96

$$V(x) = \sum_{i=1}^M n_i(x) \quad (15)$$

Once the aggregated preference function is constructed, the original multi-criteria optimization problem in this decision-making process can be transformed into a single criterion optimization problem taking multiple constraints into account.

$$\begin{aligned} \min_x J(x) &= \min V(x) \\ \mathbf{h}_I(\mathbf{x}) &\leq \mathbf{h}_I && \text{for inequal constraints} \\ \text{s.t. } \mathbf{h}_E(\mathbf{x}) &\leq \mathbf{h}_E && \text{for equal constraints} \\ \mathbf{x}_{\min} &\leq \mathbf{x} \leq \mathbf{x}_{\max} && \text{for designed variables} \end{aligned} \quad (16)$$

In this study, $\mathbf{x}$ represents the preference variables of existing launch systems defining the launch opportunity.

Currently, four indices (i.e., launch cost, predicted reliability, total launch times and availability) are adopted to evaluate the launch opportunity, with the first one categorized into Type-1 and the others into Type-2. The preferences of each criterion based on expert opinion are described in Table 6. Since the demand is high efficiency, we set MTBM = 30 d in the definition of availability so that this attribute becomes 100% if the launch system is operable within one month.

Applying the method developed, both categories of current launch systems are ranked by their preference values. The results are shown in Table 7 and Table 8. For each category, a comparison of the performance of the top six systems is displayed using radar charts in Figs. 10 and 11. By investigating the ranks of Pegasus (fifth with one B, two C and one D) and Minotaur IV (sixth with one A, one B, one C and one E) in Fig. 10, it is indicated that balanced development on all of the attributes leads to a higher aggregated preference value. Additionally, since the evaluating images α_k are the same for both the small and medium and intermediate launch systems, the graphical quantitative comparison con-

Table 7. Preference ranking of active small launch systems with preference ranges.

Vehicle	LEO cost (FY2010\$K)		Predicted reliability (%)		Total launches		Availability		$V(x)$
	$n_1^1(x)$	Range	$n_2^2(x)$	Range	$n_3^3(x)$	Range	$n_4^4(x)$	Range	
Kosmos 3M	0.0184	A	0.0236	B	0.0164	A	0.0083	A	0.0667
Rocket	0.0163	A	0.1892	C	0.2891	C	0.2116	C	0.7061
Vega	0.0498	B	0.080	C	1.2116	D	0.0793	B	1.4207
Pegasus	1.0532	D	0.2151	C	0.1947	C	0.0783	B	1.5413
Pegasus XL	0.9636	D	0.2398	C	0.2740	C	0.0795	B	1.5568
Minotaur IV	0.0191	A	0.2398	C	1.2800	E	0.0621	B	1.6011
Minotaur I	0.4455	D	0.0658	B	1.1121	D	0.3143	C	1.9378
START	0.0612	B	0.1892	C	1.2600	D	1.2354	D	2.7458
Taurus	0.0569	B	2.0183	E	1.1825	D	1.0955	D	4.3533
KZ	0.0154	A	0.3200	D	3.7255	E	0.6905	D	4.7515
Volna	0.0177	A	3.6761	E	1.2800	E	1.2297	D	6.2035
Shavit 1	1.4446	E	2.1366	E	1.2600	D	2.2154	E	7.0567
Epsilon	0.2849	C	1.0218	D	4.3834	E	2.4412	E	8.1313
Strela	0.0160	A	0.3200	D	3.7255	E	4.7158	E	8.7773
Shtil 1	0.0291	B	1.0218	D	4.3834	E	5.1200	E	10.554
Taurus XL	0.2197	C	3.8364	E	3.7255	E	2.9695	E	10.751

Table 8. Preference ranking of active medium-sized launch systems with preference ranges.

Vehicle	LEO cost (FY2010\$K)		Predicted reliability (%)		Total launches		Availability		$V(x)$
	$n_1^1(x)$	Range	$n_2^2(x)$	Range	$n_3^3(x)$	Range	$n_4^4(x)$	Range	
Soyuz U	0.0144	A	0.0156	A	0.0088	A	0	A	0.0387
Delta 2	0.0198	A	0.0149	A	0.0199	A	0.0192	A	0.0738
Soyuz 2	0.0132	A	0.0766	B	0.0742	B	0.0191	A	0.1831
Long March 2C	0.0163	A	0.0195	A	0.2151	C	0.1569	C	0.4078
Delta 2M	0.0600	B	0.0158	A	0.2740	C	0.0755	B	0.4252
Long March 2D	0.0116	A	0.0162	A	0.2844	C	0.1638	C	0.4761
Dnepr	0.0093	A	0.0711	B	0.3174	C	0.1067	C	0.5045
Long March 3A	0.0166	A	0.0179	A	0.3085	C	0.2321	C	0.5750
Long March 4C	0.0179	A	0.0759	B	0.4505	D	0.0760	B	0.6202
PSLV-XL	0.0106	A	0.0406	B	0.9058	D	0.0770	B	1.0341
Long March 3C	0.0178	A	0.0406	B	0.9058	D	0.0778	B	1.0421
PSLV-CA	0.0136	A	0.0658	B	1.1122	D	0.2023	C	1.3938
PSLV-G	0.0108	A	0.5959	D	1.0698	D	1.0870	D	2.7635
Delta 4M	0.0165	A	0.3200	D	3.7255	E	0.9119	D	4.9739
GSLV	0.0155	A	3.2131	E	1.1495	D	0.7846	D	5.1628

Fig. 10. Comparison of preference towards active small launch systems.

Fig. 11. Comparison of preference towards active medium and intermediate launch systems (S-U denotes Soyuz U and D-2 denotes Delta 2, which rank 1st and 2nd place, respectively, with coinciding lines in the chart).

cludes that the overall performance of the latter group is better than the smaller competitors.

For example, the average amount of unit LEO cost of the medium group is only 42.40% of that of small systems, while the average total launch time of the medium-sized systems is 2.31 times that of the other group.

4. Case Study

In order to demonstrate the capability of the method proposed, two classical launch cases of small satellites are re-

Table 9. Comparison of the potential launch vehicles for the Flock 3p mission.

Mission	Expected launch vehicle	Total cost (FY2010\$K)	Predicted reliability (%)	V(x)
Flock 3p	PSLV-XL	2192.08	94.12	1.0341
Small	Kosmos 3M	5004.56	94.87	0.0667
	Rockot	3929.20	87.50	0.7061
	Vega	7362.08	90.00	1.4207
	Pegasus XL	17164.40	85.71	1.5413
	Minotaur IV	5500.88	85.71	1.6011
Medium	Soyuz U	3226.08	97.20	0.0387
	Delta 2	6038.56	97.41	0.0738
	Soyuz 2	2853.84	90.77	0.1831
	Long March 2C	3929.20	95.35	0.4078
	Delta 2M	7982.48	97.14	0.4252

Table 10. Comparison of the potential launch vehicles for the Formosat-2 mission.

Mission	Expected launch vehicle	Total cost (FY2010\$K)	Predicted reliability (%)	V(x)
Formosat-2	Taurus-XL	12380.80	40.00	10.751
Small	Kosmos 3M	9244.40	94.87	0.0667
	Rockot	7258.00	87.50	0.7061
	Vega	13599.20	90.00	1.4207
	Minotaur IV	10161.20	85.71	1.6011
	Taurus	14363.20	63.64	4.3533
Medium	Soyuz U	5959.20	97.20	0.0387
	Delta 2	11154.40	97.41	0.0738
	Soyuz 2	5271.60	90.77	0.1831
	Long March 2C	7258.00	95.35	0.4078
	Delta 2M	14745.20	97.14	0.4252

viewed with their launch vehicles reconsidered by the aggregated preference value function. The only constraint in Eq. (15) considered is the LEO payload capacity. The comparison is shown in Table 9 and Table 10.

The first case is a well-known constellation launch mission, Flock 3p, consisting of 88 cubesats, each weighing 4.7 kg.²¹⁾ This constellation was launched by PSLV-XL on 15 February 2017. As is shown in Table 9, we can clearly notice that the outstanding advantage of PSLV-XL is the low cost, which might be the driving factor for Planet Labs to choose it. Simultaneously, one factor that cannot be ignored is its unsatisfactory performance in availability, which puts a negative impact on PSLV-XL's aggregated preference ranking (shown in Table 8). Since this was not an emergency mission, the company's decision leaned towards the cost characteristic. Generally, the Soyuz U is recommended by the preference model for this launch mission in terms of its comprehensive capability.

As is shown in Table 10, the Taiwanese small satellite Formosat-2,²²⁾ launched using the Taurus XL in 2004, is demonstrated as the second case. Through preference analysis, this launch strategy cannot be considered a sensible one, since none of the attributes of the Taurus XL is superior. By comparing the aggregated preference value of active launch vehicles, Kosmos 3M, Rockot, Soyuz, Delta 2 and Long

March 2C are the top five candidates with convincing performance in such characteristics as cost, reliability, availability, and so on. With any of these potential candidates as a replacement of the launch vehicle of satellite Formosat-2, financial cost as well as potential waiting time could have been saved for launch operation and preparation. However, one condition that cannot be ignored is that political and other non-performance reasons also influence the decision-making process, which might account for the final choice of Formosat-2, yet does not fall within the scope of this paper.

5. Conclusions

The miniaturization of satellites makes it easier to obtain access to space, yet problems still exist in finding the best launch opportunity for entering space, and this is constrained by concrete or abstract considerations. The aim of this paper was to identify, quantify and evaluate the key concerns of small satellite launch opportunities using an aggregated preference value model applied from the perspective of the user. Such a task could be an initial point of exploration toward the decision-making process when studying small satellite launch opportunities.

Based on our previous research, we updated a launch system capability database that extracts main attributes in two categories: small and medium and intermediate launch vehicles. Subsequently, the definition of the availability of launch opportunity was identified as well as the predicted reliability that allows for further assessment of launch capabilities. This analysis has shown a positive relation between the larger total number of launch attempts and small average launch cycle, as well as greater availability towards launch opportunities. Finally, an aggregated preference value model was proposed to integrate and evaluate the key user-defined objectives of the classified launch vehicle. Our results show that a higher preference tendency exists towards launch systems with balanced development in all aspects (e.g., cost, total launch times, reliability and availability). All in all, there still exists a big opportunity for dedicated launchers to develop technologies and to catch up with the larger competitors in the global market.

This method allows launch opportunities to be estimated without an interdisciplinary trade-off and brings in a simple but concrete index for decision-making. Moreover, the aggregated preference value method developed here provides not only an approach for users to choose from different options, but also a chance for launchers to re-examine their positioning in the demanding global market. Therefore, the method proposed can help select an appropriate launch opportunity for a given mission and obtain a better understanding of the current small satellite launch market.

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