Launch Vehicle Classification for Decision-Making of Small Satellite Launch Options*

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In recent years, there has been a steady increase in the small satellite launch market. With the rapid development of novel launchers, for small satellite owners and operators, how to effectively and efficiently choose appropriate launch vehicles has become a major concern. Based on updated launch records, a reliable launch data source for multi-attribute evaluation and recategorisation is established. Using a statistical classification process, active launch vehicles are classified into five representative-in-class launchers on the basis of their capabilities and performance. Unlike the previous categorisation based on payload ability, this method captures launch cost, technology maturity, reliability and availability of each category within the current launch vehicles in service. Moreover, representatives are selected as the baseline types for the high-level planning and designing of complex small satellite launch missions. The analysis indicates that this study provides a valid statistical classification and selection strategy of representative-in-class launch vehicles to support decision-making for rapid assessment on a large number of small satellite launch missions.

Key Words: Small Satellite, Launcher Selection, Reliability, Launch Cost

1. Introduction

The past decade has witnessed a boom in the small satellite market. Definitions of small satellites are various across multiple organizations. To keep consistent with the description in the symposium1) on small satellite missions, the class of satellites weighing less than 1,000 kg is defined as small satellites in this research.

This boom is stimulated by the lowered cost of space system design and development due to the rapid growth of emerging technologies such as commercial-off-the-shelf (COTS) products.2,3) Thanks to COTS components, the cost of developing a typical small satellite has been reduced to roughly $10,000/kg.4) As seen in Fig. 1, the number of satellites launched has enjoyed a sharp increase from 2012, especially for small satellites that contribute to major market shares.

Additionally, more and more innovative launch vehicles have appeared in recent years; for example, Long March 5, Long March 11, Falcon 9, and Falcon Heavy.5–7) The wide assortment of launch vehicles available today affords space launch opportunity seekers numerous deployment options, each of which has its superiorities in different aspects such as payload capability, launch cost, and launch availability. For example, the Falcon family has demonstrated both technical and practical feasibility of reusable launch vehicles, of which the Falcon Heavy has the largest payload capability.

This indeed has created an extremely competitive environment for launch service providers worldwide.

Since launch options have become diversified recently, there are inherently great opportunities offered for space launches of small satellites. However, high mission cost, especially launch cost, is probably the most significant limitation to small scientific satellites. Unlike large satellite operators whose development and management approaches tend to emphasise low risk and high reliability, small satellite developers are usually more concerned about the cost issue and allow for experimentation, risk-taking, and failure.8) Under these circumstances, for small satellite operators, how to effectively and efficiently choose appropriate launch vehicles has become their primary concern. Typically, there are three launch approaches: dedicated, rideshare, and piggyback launches.9,10) Rideshare refers to the method of launching...
multiple similar-sized payloads into orbit by sharing a single vehicle, while piggyback only transmits a small portion of the launching cost or receives a complementary opportunity as a secondary payload. However, rideshare and piggyback launches involve substantial uncertainty out of the reach of the technical level. Thus, efforts of this research focus on the evaluation and optimization of dedicated launches. Specifically, based on the reliable launch database established, a statistical classification process is utilized to analyze different launch performances and support the decision-making of small satellite launch options.

The remainder of this paper is organized as follows. Section 2 begins with a description of the current active launch vehicles and their traditional classification based on the LEO payload capabilities. Next, the methodology implemented in this research is presented in Sections 2.2 and 2.3, including the selection of variables for launch vehicle re-classification and the statistical classification process. Results and analysis of the classification are provided in Section 3, based on which we propose a Launch Opportunity Metric (LOM) for quick assessment of the performance between and within each category. Section 4 gives some concluding remarks of the current work.

2. Methodology

2.1. Launch vehicle database

The launch vehicle database was obtained using the launch data from the International Reference Guide to Space Launch Systems,39 and on-line space launch system data.10,11,12 Here, we define the metric of unit cost by dividing the total cost by the maximum payload. Please note that the cost per kg actually used may be different from what is reported due to the amount of wasted payload capacity every launch.13 Before the re-classification, launch systems are presented following the three classical classifications defined in The New SMAD according to their payload capability to LEO; namely, small launch systems (<5,000 lb), medium ([5,000 lb, 12,000 lb]), intermediate launch systems ([12,000 lb, 25,000 lb]) and heavy launch systems (≥25,000 lb). As of 16th March 2019, the different concerned properties of selected launch systems are exhibited in Table 1, Table 2 and Table 3, to cover the most significant performance indexes.

2.2. Variables for launch vehicle re-classification

A selection of variables to demonstrate the capabilities of current active launch systems is listed in Tables 1–3. They were later used for the clustering analysis. Five representative variables are shown in Table 4 for the performance assessment of launch systems at the vehicle level. Please note that the performance variables shown in Table 4 are used in the clustering process under the assumption that they are relevant for evaluating the launch opportunity.

The launch performance of a commercial launch vehicle system is inherently linked to parameters defining its characteristics.14,15 According to the results of the previous analysis, the basic launch capability for future mainstream small satellite missions is to launch a small satellite into the LEO within an altitude of 1,500 km.16 Therefore, the transportation ability and the economic cost are measured by LEO payloads and the unit LEO price in this study.

Reliability is one of the most critical factors in evaluating a launch vehicle for use. It denotes a launch vehicle’s state of having a low risk of technical failure based on a history of prior mission successes. Satellite operators are generally unwilling to neither accept additional risks nor to purchase extra insurance with the first few launch attempts. Therefore, two metrics, namely the total launch times and current reliability (i.e., successes rate) are introduced to measure the system reliability in this performance evaluation process.

As for the availability, which presents the compatibility of the launch schedule between launchers and small satellite operators, a detailed analysis of this metric can be found in our previous research.15,16 It has been shown that the sample mean launch cycle is preferred to indicate the level of availability of launch opportunities.

2.3. Statistical classification process

Under the assumption that performance variables are inde-

| Vehicle | Country | Capacity (kg) | Unit cost (FY2010$K) | Total launches | Reliability (%) | Average launch cycle (days) | Last launch date (DDMMYYYY) |
|---------|---------|---------------|-----------------------|----------------|-----------------|----------------------------|---------------------------|
| Epsilon | Japan  | 1,200         | 450                   | 31.7           | 84.4            | 4                          | 100.00                    | 651                        | 18/01/2019                |
| Kosmos 3M | Russia | 1,500         | 775                   | 12.1           | 23.7            | 446                       | 95.07                     | 35                        | 27/04/2010                |
| Kuuizhou | China  | 1,500         | 1,000                 | 8.7            | 13.1            | 4                          | 100.00                    | 610                       | 29/09/2018                |
| Minotaur I | USA    | 607           | 317                   | 35.9           | 68.7            | 11                         | 100.00                    | 505                       | 20/11/2013                |
| Minotaur IV | USA    | 1,650         | 1,000                 | 13.3           | 22              | 6                          | 100.00                    | 447                       | 26/08/2017                |
| Pegasus | USA    | 375           | 161                   | 43.1           | 100.4           | 43                         | 88.37                     | 232                       | 15/12/2016                |
| Rockot | Russia | 1,950         | 1,000                 | 9.5            | 18.5            | 32                         | 90.63                     | 330                       | 30/11/2018                |
| Shavit 1 | Israel | 350           | —                     | 58.5           | —               | 6                          | 66.67                     | 1,166                     | 06/09/2004                |
| START | Russia | 632           | 167                   | 19.5           | 73.6            | 6                          | 100.00                    | 956                       | 25/04/2006                |
| Strela | Russia | 1,560         | 700                   | 9.2            | 20.5            | 3                          | 100.00                    | 2,016                     | 19/12/2014                |
| Taurus XL | USA    | 1,590         | 860                   | 28.5           | 52.6            | 3                          | 33.33                     | 1,270                     | 04/05/2011                |
| Taurus | USA    | 1,380         | 720                   | 18.8           | 35.9            | 10                         | 70.00                     | 956                       | 31/10/2017                |
| Vega | Italy  | 1,963         | 1,395                 | 17.8           | 25.1            | 13                         | 100.00                    | 206                       | 21/11/2018                |
| Volna | Russia | 140           | 40                    | 11.2           | 39.3            | 5                          | 40.00                     | 944                       | 06/10/2005                |

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

| Type     | Vehicle       | Country | Capacity (kg) | Unit cost (FY2010$K) | Total launches | Reliability (%) | Average launch cycle (days) | Last launch date (DDMMYYYY) |
|----------|---------------|---------|---------------|-----------------------|----------------|-----------------|---------------------------|-----------------------------|
| Medium   | Delta 2       | USA     | 5,144         | 3,123                 | 14.6           | 24.0            | 114                       | 97.44                       | 92                          | 18/11/2017                  |
| Medium   | Delta 2M      | Russia  | 3,158         | 1,998                 | 19.3           | 30.8            | 34                        | 100.00                      | 228                         | 15/09/2018                  |
| Medium   | GSLV          | India   | 5,000         | —                     | 8.8            | —               | 13                        | 61.54                       | 538                         | 19/12/2018                  |
| Medium   | CZ 2C         | China   | 3,200         | 2,000                 | 9.5            | 15.3            | 50                        | 98.00                       | 269                         | 29/10/2018                  |
| Medium   | CZ 2D         | China   | 3,500         | 1,300                 | 5.9            | 15.8            | 43                        | 97.67                       | 229                         | 29/12/2018                  |
| Medium   | CZ 4C         | China   | 4,200         | 1,700                 | 11.4           | 28.1            | 25                        | 96.00                       | 184                         | 20/05/2018                  |
| Medium   | PSLV-CA       | India   | 2,800         | 1,100                 | 7.2            | 18.3            | 13                        | 100.00                      | 353                         | 29/11/2018                  |
| Medium   | PSLV-G        | India   | 3,700         | 1,050                 | 5.4            | 19.2            | 12                        | 83.33                       | 764                         | 26/09/2016                  |
| Medium   | PSLV-XL       | India   | 3,800         | 1,750                 | 5.3            | 11.5            | 20                        | 95.00                       | 182                         | 11/04/2018                  |
| Inter.   | Delta 4M      | USA     | 9,144         | 6,593                 | 9.7            | 13.4            | 3                         | 100.00                      | 667                         | 04/11/2006                  |
| Inter.   | CZ 3A         | China   | 6,000         | 5,000                 | 9.8            | 11.8            | 27                        | 100.00                      | 343                         | 09/07/2018                  |
| Inter.   | CZ 3C         | China   | 9,100         | 6,500                 | 11.3           | 15.8            | 16                        | 100.00                      | 260                         | 24/12/2018                  |
| Inter.   | Soyuz 2       | Russia  | 7,900         | 4,850                 | 6.9            | 11.3            | 83                        | 91.57                       | 64                          | 27/02/2019                  |
| Inter.   | Soyuz U       | Russia  | 7,000         | 4,300                 | 7.8            | 12.7            | 786                       | 97.33                       | 20                          | 22/02/2017                  |

Table 3. Active heavy launch systems (heavy launch vehicles are identified by their payload capabilities to LEO (≥25,000 lb)).

| Vehicle   | Country | Capacity (kg) | Unit cost (FY2010$K) | Total launches | Reliability (%) | Average launch cycle (days) | Last launch date (DDMMYYYY) |
|-----------|---------|---------------|-----------------------|----------------|-----------------|---------------------------|-----------------------------|
| Atlas 5   | USA     | 20,050        | 8,200                 | 8.6            | 25.3            | 79                        | 98.73                       | 75                          | 17/10/2018                  |
| Delta 4 Heavy | USA     | 22,560        | 13,130                | 9.5            | 16.4            | 11                        | 90.91                       | 467                         | 19/01/2019                  |
| Ariane 5ECA | Europe  | 21,000        | 12,000                | 8.4            | 14.7            | 70                        | 97.14                       | 84                          | 05/02/2019                  |
| Delta 4M plus | USA     | 13,701        | 6,822                 | 6.5            | 13              | 25                        | 100.00                      | 92                          | 16/03/2019                  |
| Falcon 9 FT | USA     | 22,800        | 8,300                 | 2.5            | 6.8             | 49                        | 100.00                      | 24                          | 02/03/2019                  |
| H-2A      | Japan   | 11,730        | 5,800                 | 7.7            | 15.6            | 40                        | 96.67                       | 157                         | 22/10/2018                  |
| H-2B      | Japan   | 16,500        | 8,000                 | 5.4            | 11.1            | 7                         | 100.00                      | 550                         | 22/09/2018                  |
| CZ 3B     | China   | 13,600        | 5,200                 | 6.0            | 15.7            | 55                        | 94.55                       | 153                         | 09/03/2019                  |
| Proton M  | Russia  | 21,000        | 5,500                 | 6.7            | 25.7            | 102                       | 89.22                       | 63                          | 21/12/2018                  |
| Zenit 3SL | Multi.  | 15,876        | 5,250                 | 7.2            | 22.1            | 36                        | 88.89                       | 154                         | 26/05/2014                  |

Table 4. Independent variables for clustering.

| Variables                         | |
|-----------------------------------|---|
| Transportation ability            | LEO payload (kg) |
| Economic cost                     | Unit LEO price (FY2010$K) |
| Reliability                       | Current reliability (%) |
| Availability                      | Total launch times |
| Average launch cycle              | Average launch cycle (days) |

pended of each other in the launch opportunity evaluation, we use those shown in Table 4 for the clustering process. Usually, traditional classification methods of launch systems define launchers by one single physical parameter of the system’s capability; for example, payload mass, orbit type, etc. In order to classify current launch systems by evaluating comprehensively towards their performance, a hierarchical cluster analysis (HCA) based on the performance variables is conducted.

Firstly, the performance database is normalized to weigh those variables equally. Using Eq. (1), we applied unity-based normalization to scale variables into the range [0, 1].

\[ x_n = \frac{(x_i - x_{\text{min}})}{(x_{\text{max}} - x_{\text{min}})} \]  

where \( x_n \) is the normalized variable and \( x_{\text{min}} \) is the minimum value of the performance variable among all launch vehicle candidates, while \( x_{\text{max}} \) is the largest.

Secondly, the HCA is performed. Usually, the HCA is implemented based on calculating the squared Euclidean distances between the samples. It is then followed by an agglomerative or divisive method to deal with the clustering. In the agglomerative clustering, each of the samples is regarded as a separate cluster initially. At each step, the merging of clusters is performed to reduce the number of clusters so as to optimise some criterion. This procedure is conducted iteratively until all of the samples are merged into one cluster at the top.\(^{18} \)

Here, we implemented Ward’s minimum variance method, one of the mainstream agglomerative methods, for clustering.\(^{18–21} \) In Ward’s method, the merging criterion is to minimize the total within-cluster variance. The variance of a cluster is defined as the sum of the squared errors (SSE) between each sample in the cluster \( C_i \) and the centroid \( \bar{x}_i \) of the cluster; namely, the squared Euclidean distance between each sample and the centroid. The SSE can be calculated as:

\[ \text{SSE}_i = \sum_{x \in C_i} (x - \bar{x}_i)^2 \]  

At each step, a local optimization strategy is applied: all pos-
sible cluster pairs are considered and the one with the least change in the variance of the clustering is chosen. This means to merge two clusters where the change in total SSE after merging is minimized.

Suppose cluster $C_i$ and $C_j$ are two clusters being agglomerated to form cluster $C_{ij}$ and $n_i$ and $n_j$ are the corresponding cluster sizes. Then, we denote $\text{SSE}_{C\!i}$ as the sum of squared errors between the centroid of the new cluster $C_{ij}$ and its samples. Thus, the SSE of cluster $C_{ij}$ can be calculated as:

$$\text{SSE}_{ij} = \sum_{x \in C_{ij}} (x - \bar{x}_{ij})^2$$

$$= \sum_{x \in C_i} (x - \bar{x}_i)^2 + \sum_{x \in C_j} (x - \bar{x}_j)^2$$

(3)

where

$$\sum_{x \in C_i} (x - \bar{x}_i)^2 = \text{SSE}_i + \frac{n_i n_j}{(n_i + n_j)^2} (\bar{x}_i - \bar{x}_j)^2$$

(4)

$$\sum_{x \in C_j} (x - \bar{x}_j)^2 = \text{SSE}_j + \frac{n_i n_j}{(n_i + n_j)^2} (\bar{x}_j - \bar{x}_i)^2$$

(5)

Using Eqs. (4) and (5), $\text{SSE}_{ij}$ in Eq. (3) can be expressed as:

$$\text{SSE}_{ij} = \text{SSE}_i + \text{SSE}_j + \frac{n_i n_j}{(n_i + n_j)^2} (\bar{x}_i - \bar{x}_j)^2$$

(6)

Then the increase in SSE can be calculated by the formula below:

$$D(i, j) = \frac{n_i n_j}{(n_i + n_j)^2} (\bar{x}_i - \bar{x}_j)^2$$

(7)

Thus, the clustering strategy is to find a pair where the minimum $D(i, j)$ is chosen:

$$i, j = \arg \min_{i \in [1, m]} D(i, j)$$

(8)

where $m$ is the current number of clusters.

Therefore, by using this general agglomerative hierarchical clustering procedure, the pairs of clusters are merged iteratively aiming at minimizing the increase in total within-cluster variance. This clustering procedure can be visualized by a tree structure called the dendrogram, of which the y-axis indicates the change in squared Euclidean distance.

According to the deduction above, it is obvious to find out that the total within sum of the squared errors, namely $\text{SSE}_{\text{total}}$, increases during the merging process. In the first step when each sample forms a cluster, the $\text{SSE}_{\text{total}}$ is equal to zero, while it reaches the highest value at the terminal step when the cluster number is one. Thus, by calculating $\text{SSE}_{\text{total}}$ at each step, the optimal value can be recognized by identifying the increasing speed of $\text{SSE}_{\text{total}}$. The idea is to find a lower SSE with the cluster number value as small as possible, which looks like the “elbow” in the line chart of the SSE. This is called the elbow method, which is commonly used to determine the number of clusters.21 The results demonstrated in Fig. 2 indicate that the “elbow” of the SSE line chart is located at the point where the number of clusters is five.

3. Results

3.1. Classification based on performance variables

The dendrogram using Ward linkage with the squared Euclidean distance as the measurement unit is shown in Fig. 3. According to the explanation in Section 2.3, here we used five as the clustering number. From Fig. 3, it is worth noticing that most of the categories are consist of launch systems from different payload types. This means that the classification is no longer embodying a single criterion–LEO payload mass. A comprehensive criterion towards multiple concerns is effecting the classification result.

By calculating the squared Euclidean distance within each category, the candidate nearest to the centroid of one category is selected as the representative. Five categories’ representatives are given in Table 5, except for Category 4. Please note that there are only two candidates in this category, so it is unnecessary to find one launch system to represent both of them. The median values of performance variables in each category are also provided in Table 5, with the optimal marked in bold fonts.

Figure 4 demonstrates the performance for the LEO payload capability and unit LEO cost of re-classified launch systems. A clear trend found in Fig. 4 is that the more a launch vehicle can carry in one launch, the less the unit cost is. Similarities can also be found in Fig. 5, where there is nearly a linear relation between the common logarithm of total launch times and the common logarithm of the average launch cycle. Two commons found in the analysis can be summarized:

- The more payload a launch vehicle can carry in one launch, the lower the LEO cost.
- The more a launch system is operated, the shorter the average launch cycle it will have.

Other characteristics that can be concluded from the box plots of performance variables of each category shown in Figs. 6 to 10 include:

- Most of the launch vehicles in Category 1 have low unit launch costs with reliabilities higher than 90% (seen in Fig. 7 and Fig. 8). Compared with other categories, it has a relatively higher payload launch ability with a LEO payload mass more than 10,000 kg, which can be found in Fig. 6. Another characteristic of launchers in this category is that their total launch times vary from several to more than 100, as is depicted in Fig. 9. As a cluster con-
sisting of heavy launch vehicles, this category can be the best option for a large bundle of small satellites launch missions.

- Category 2 has a relatively higher unit launch cost ranging from US$10,000 FY2010 to US$60,000 FY2010 with a smaller launch payload capability (less than 5,000 kg) (seen in Fig. 6 and Fig. 7). However, from Fig. 9 and Fig. 10, launch systems in this category have fewer launch attempts and have a wide range in the value of the average launch cycle, which displays their instability in availability performance.

- Shown in Fig. 7 and Fig. 8, Category 3 has the lowest current reliability among all categories. However, it has a relatively low LEO unit cost. Since this category consists of small and medium launch vehicles, its transportation ability is limited to less than 5,000 kg for LEO orbit missions. Meanwhile, as demonstrated in Fig. 9 and Fig. 10, a small number of launch times and a longer launch cycle imply its limited launch experience compared with other categories.

- The extremely high number in total launch times and low number in average launch cycle made Soyuz U and Kosmos 3M a unique category; namely, Category 4 (seen in Fig. 9 and Fig. 10). In contrast with Category 3, this category has impressive superiorities in launch experience and availability. From Figs. 6 to 8, Category 4 also has good performance in terms of other aspects of launch option evaluation, including LEO payload capability, LEO

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**Table 5.** Representative-in-class launch systems for each category.

| Category | LEO payload (kg) | Unit LEO price (FY2010K) | Current reliability (%) | Total launch times | Average launch cycle (days) | Representative Original type | First flight (DD/MM/YYYY) |
|----------|------------------|---------------------------|-------------------------|--------------------|-----------------------------|-----------------------------|--------------------------|
| 1        | 18,275           | 6.95                      | 96.90                   | 45                 | 120                         | Atlas 5 Heavy               | 21/08/2002               |
| 2        | 620              | 33.80                     | 100.00                  | 6                  | 803                         | Epsilon Small               | 14/09/2013               |
| 3        | 1,590            | 11.20                     | 61.54                   | 10                 | 944                         | Taurus Small                | 13/04/1994               |
| 4        | 4,250            | 9.95                      | 96.20                   | 616                | 28                          | Kosmos 3M Small             | 15/05/1967               |
|          |                  |                           |                         |                    |                             | /Soyuz U Inter.             | 18/05/1973               |
| 5        | 3,500            | 9.70                      | 100.00                  | 25                 | 260                         | CZ 2C Medium                | 09/09/1982               |

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**Fig. 3.** Dendrogram using Ward’s linkage.

**Fig. 4.** LEO unit cost and LEO payload of different categories.

**Fig. 5.** Total launch times and average launch cycle of different categories.
unit price, and current reliability, which made these two launch systems almost the most ideal launch options for small satellite ventures.

- Category 5 has relatively average performance for all performance properties, which is presented in Figs. 6 to 10. Although this category consists of four different types of launch vehicles when it refers to payload capabilities, box plots in Fig. 6 show that it has a relatively narrow payload capability distribution as compared to Category 1 and Category 4. Launch vehicles classified in this category, especially those located within the “boxes” (i.e., between $Q_1$ and $Q_3$, the lower and upper box outlines), share the common features of not outstanding but sufficient payload launch capability, low LEO unit price, good history launch success rate, not that mature but sufficient launch experience, and accessible launch activity.

### 3.2. Launch opportunity metric

Although the database in Section 2.1 has provided practical indices to measure the capabilities of launch systems, it is still less instinct to demonstrate the overall performance of each option. Moreover, the basic concern of finding the best launch vehicle is still unsolved, even with the results of reclassification and extraction. Efforts still need to be made to propose a comprehensive and straightforward evaluation method.

Focusing on the basic needs of small satellite constructors, a launch opportunity metric (LOM) is proposed to assess launch systems comprehensively. Based on the database constructed in Section 2.1 and the analysis conducted in Section 2.2, this performance-related metric is built using the five variables representing launchers’ performance from four aspects: payload capability, affordability, reliability, and availability.

Prior to model establishment, each of the five performance variables needs to be classified in accordance with their contribution to the evaluation of a launch option. According to the theory of physical programming, types of different attributes depend on the preference of the decision-makers. In this study, there are two basic criteria of preferences to distinguish variables: 1) Type-1: smaller is better, and 2) Type-2: larger is better. As for the launch option, a vehicle that has better launch capability with a lower price and an outstanding historical launch record is always more desirable. Meanwhile, availability is another significant aspect, which here is represented by two variables: the total launch times and the average launch cycle. Generally, launch systems with a larger number of launch times and a shorter average launch cycle are considered as more available. A detailed derivation and explanation can be accessed from previous research. Therefore, these five variables can be classified...
into two types: 1) Type-1: LEO unit cost and average launch cycle, and 2) Type-2: LEO payload capability, reliability, and total launch times.

Next, the LOM can be calculated as the sum of weighted normalized performance variables:

\[
LOM = \sum_{i=1}^{5} (w_i \cdot p_i), \quad i = 1, 2, \ldots, 5
\]  

(9)

where \(p_i\) is the \(i\)th normalized performance variable and \(w_i\) is the corresponding weight. Please note that \(w_i < 0\) when \(i\) equals 2 or 5, and \(w_i > 0\) when \(i\) equals 1, 3 and 4. This differentiates the opposite contribution from the Type-1 variables and Type-2 variables towards a launch opportunity.

As a preliminary attempt, the absolute values of all weighting factors \((w_j)\) are set to be 1. Then, the LOMs of launch vehicles in each category can be calculated using Eq. (9). Subsequently, the average value of LOMs in every category is regarded as the sample mean. Here are the sample means of LOMs for each category: 1.62, -0.07, -0.18, 1.77 and 0.91.

Box plots in Fig. 11 present the spread of LOMs of the five categories. As is shown in Fig. 11, median values are indicated by the solid red horizontal lines, while the lower and upper quartiles (\(Q_1\) and \(Q_3\)) are at the lower and upper box outlines. Additionally, lower and upper fences (e.g., quartiles \(\pm 1.5\text{IQR}\), where IQR = \(Q_3 - Q_1\)) are also depicted by the short horizontal lines outside of the boxes. One outlier in Category 2, namely the launch system START, is indicated by a red cross.

Fig. 11. Box plot diagram with the launch opportunity metric (LOM) (with \(|w| = 1\)) for each category.

Box plots in Fig. 11 present the spread of LOMs of the five categories. As is shown in Fig. 11, median values are indicated by the solid red horizontal lines, while the lower and upper quartiles (\(Q_1\) and \(Q_3\)) are at the lower and upper box outlines. Additionally, lower and upper fences (e.g., quartiles \(\pm 1.5\text{IQR}\), where IQR = \(Q_3 - Q_1\)) are also depicted by the short horizontal lines outside of the boxes. One outlier in Category 2, namely the launch system START, is indicated by a red cross. By comparing the median values of the five categories, from the highest to the lowest, the between-category rank of LOMs of these five categories should be Category 4, Category 1, Category 5, Category 2, and Category 3. Furthermore, a within-category comparison is conducted by ranking the LOM values within each category. The ranking list is provided in Table 6.

As is shown in Table 6, the between-category rank of the median value of LOMs is Category 4 with 1.771, Category 1 with 1.517, Category 5 with 0.915, Category 2 with 0.124, and Category 3 with -0.146. This ranking list is the same as the between-category rank of the sample means. Thus, it is indicated that members in each category, except for the outliers and extreme points, are more likely to share common characteristics within the group they are classified.

It is also worth noticing that, although some launch vehicles from different categories have very close LOM values, they nevertheless may be far away from each other in the performance domain. For example, the LOMs of H-2B and Kosmos 3M are close to each other, yet the former belongs to Category 4 and the latter belongs to Category 3. Therefore, they have distinguished characteristics in the launch performance. If a preliminary preference towards experience rather than payload ability were conveyed from the DM, the option would be Kosmos 3M. Otherwise, if launch reliability is the most desirable, H-2B would be the ideal choice.

In this case, it is of great significance to set weighting factors properly to reflect the DM’s priori tendency using the LOM to select launch opportunities.

Associated with the results of reclassification in Section 2.1, a two-level decision-making process is introduced. As an objective evaluation of launchers’ performance, the results of the reclassification offer decision-makers launch system classes with similarities to choose from. In this step, the
initial selection is made by determining the feasible category first. Afterwards, further decision-making is conducted using the LOM ranking of those candidates in the selected category. In this way, the reclassification provides an indispensable reference for the preliminary selection, which becomes even more important when some information of concerned performance is unavailable or inaccurate.

4. Conclusions

This paper has developed and implemented a statistically based classification methodology for current active launch systems. As a result, commercial launch vehicles are reclassified into five categories based on their launch performance, including launch capability, cost-effectiveness, reliability, and availability. The five categories and the in-class representatives selected have their own characteristics and differences from other categories, showing that they are well differentiated in terms of the basic concerns from the decision-makers.

In the analysis of performance parameters, there is an inverse relationship between LEO payload capability and affordability. Moreover, another significant performance attribute, namely availability, can be decided roughly using only one variable; that is the total number of launch times. These two conclusions, which are shared by all of the active launch systems, will allow decision-makers to make a preliminary assessment towards the launch opportunity with limited accessible information.

Based on the reclassification results, a single metric to provide a quick view of overall performance is proposed. Unlike the clustering method, which assesses launch options from an abstract aspect through the simplification of the launch systems in service into five appropriate representatives, this metric, namely the launch opportunity metric (LOM), provides a more concrete quantified approach and a clear in-class ranking of the launch systems in each category. In this way, a two-level decision-making framework is formed. Firstly, the DMs can make a rough choice by comparing the performance parameters of the five in-class representatives and deciding their preferred category. Secondly, a refined selection can be implemented by ranking the members in that target category with the LOM value.

With the growth of the future launch market, the reclassification and simplification proposed in this paper can enable the analysis, rapid design and optimization of launch plans for a large number of small satellites taking into consideration launch cost, efficiency and reliability. Moreover, this methodology also enables access to a high-level examination of the launch options available at the system level in terms of launch technology developments.

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