Trans. Japan Soc. Aero. Space Sci.
Vol. 62, No. 4, pp. 175–183, 2019
DOI: 10.2322/tjsass.62.175

Launch Cost Analysis and Optimization Based on Analysis of Space System Characteristics*

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The rapid developments in micro-technologies and the introduction of modularity and standardization into system designs, present significant opportunities for cost reduction in the design and development of satellite systems. However, the high cost of space launch has become a major hindrance to capitalizing on these opportunities. Therefore, seeking appropriate launch opportunities and reducing launch costs might contribute to further growth of the space market. This paper focuses on the analysis of dedicated launch costs factoring in the effect of launch reliability, which in return, can enable the optimization of system designs. Applying a value-centric architecture, system characteristic space is introduced as the design space to define the characteristics of different systems. Based on our launch vehicle database, the launch cost and reliability of different families of launch vehicles are investigated, where the reliability is calculated using a modified two-level Bayesian analysis. The factors of launch cost and reliability are subsequently integrated into the expected launch cost, acting as the objective function for the analysis and optimization process associated with the manufacturing cost of satellites. Through reviewing and redesigning a few classical launch cases, the effectiveness and applicability of the design architecture proposed are validated.

Key Words: Conceptual Design, Dedicated Launch Cost, Value-centric Design, System Characteristic Space

1. Introduction

Due to the rapid development of micro-technologies and the introduction of modularity, a boom in the utilization of small satellites has been witnessed in the past two decades, driving growth in the space market. As shown in Fig. 1, the Union of Concerned Scientists (UCS)[1)] revealed that the number of small satellites launched has continued to increase sharply since 2012, contributing to the constant increase in the total number of satellites launched. The State of the Satellite Industry Report 2016[2)] also pointed out the continued and growing global interest and expenditure in inexpensive platforms.

Since commercial off-the-shelf (COTS) products have lowered the threshold of spacecraft design and development, satellite manufacturers are realizing significant opportunities for cost reduction. However, the high cost of launch seems to be in opposition to this trend. For instance, developing a typical small satellite costs roughly $10,000 per kg,[3)] while the dedicated launch cost can be much more expensive (e.g., almost double for the European small launch vehicle Vega).[4)] Consequently, seeking an appropriate launch opportunity and reducing launch cost might lead to further growth of the space market.

The current launch opportunities are divided into three categories: dedicated, rideshare, and piggyback launches.[5)] Since the latter two options involve too much uncertainty beyond the technical level, the research efforts of this paper focus on the dedicated launch cost analysis and optimization for both small and large space systems. It is worth noting that this approach could also be further adapted for piggyback and rideshare launches if the corresponding data were available.

The remainder of this paper is organized as follows. In Section 2, "value-centric design architecture" is introduced to describe the general process for the quantitative design, analysis, and optimization of space system launch cost. Under this design architecture, the system characteristic space, consisting of the degree of duplication, fractionation, and derivation, is presented in Section 3 as the design space to define the characteristics of different systems and enable the optimization of system designs. Based upon our launch

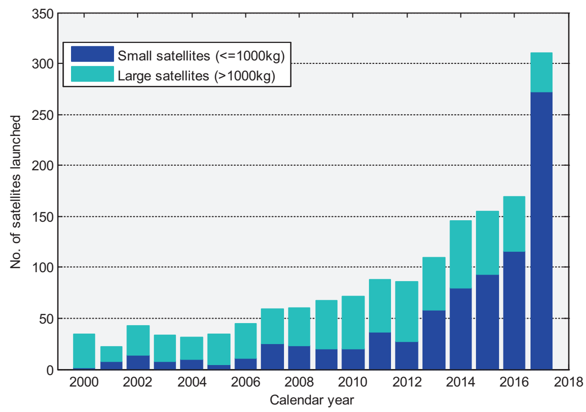

Fig. 1. Recent launch history of the satellites recorded in the UCS satellite database.[1)]

*Presented at the 31st International Symposium on Space Technology and Science, 3–9 June, 2017, Matsuyama, Japan.
Received 22 June 2017; final revision received 12 April 2018; accepted for publication 13 November 2018.
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vehicle database, Section 4 models and analyses the launch cost and reliability of various families of launch vehicles. Finally, the expected development and deployment cost is proposed as the objective function to enable the optimization process, with the case studies shown in Section 5 and the conclusions presented in Section 6.

2. Value-centric Design Architecture

To enable the quantitative analysis and optimization of the system design using both traditional and innovative concepts and technologies, a value-centric design architecture based on system characteristic space is presented.

The basic value flow process in the architecture is shown in Fig. 2. Overall, system value is accumulated from the bottom to the top. It reflects certain design characteristics of space systems. At the subsystem level (System level 3), the value within each subsystem is generated from subsystem properties, such as mass, size, and reliability. The subsystem value is subsequently integrated at the spacecraft level (System level 2). The integrated spacecraft value also influences the value characteristic of the corresponding launch activities (System level 1). Finally, the value of the three system levels is synthesized into the overall system value.

Specifically, in this research, the system property of concern is mass and the corresponding value is the expected launch cost. Through exploring the feasible domain of design variables, namely, different system designs, the analysis and optimization of the launch cost of a space system can be achieved.

Under the value-centric design architecture proposed by Collopy,[6] the specific approaches and techniques of launch cost analysis (Fig. 3) are described as follows.

(1) Elaborate. Through the elaboration process, formulation of the system characteristic space and the overall system configuration definition are established, as well as their transformation relationship.

(2) Analyze. In the analysis process, the system configuration characteristics such as duplication and distribution are analyzed to identify the integration philosophy of the mass properties.

(3) Evaluate. The evaluation process integrates the launch cost value utilizing the appropriate system value models to determine whether or not system requirements are met.

(4) Optimize. In the optimization process, an appropriate optimization algorithm is applied to reach the best solution by quantifying launch cost as the objective function.

3. System Characteristic Space

The system characteristic space,[7] consisting of duplication, fractionation, and derivation, is introduced to capture and reflect the configuration characteristics of different system designs. Through the system characteristic space proposed, the mapping relationship between a set of conceptual designs and the corresponding system characteristics is established. This enables the quantitative analysis and optimization of space system design under the value-centric architecture.

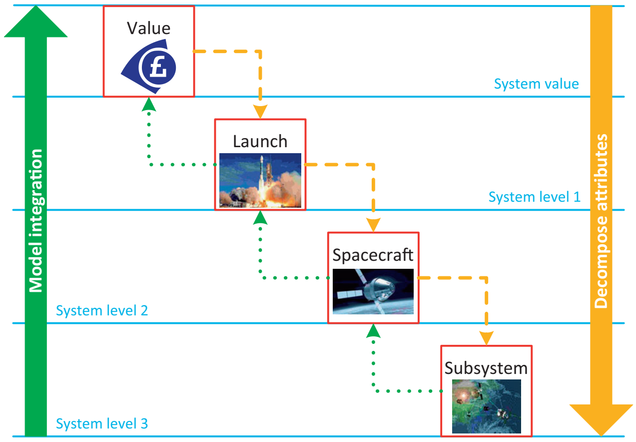


Fig. 2. Value flow diagram.

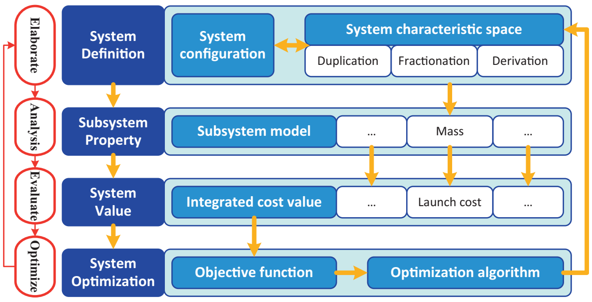


Fig. 3. Value-centric design architecture.

The system characteristics are divided into two dimensions: homogeneous and heterogeneous degrees. The homogeneous degree is mathematically defined as the number of identical or near identical components, subsystems, or satellites in a space system; namely degree of duplication. Duplication is widely used to realize an ambitious function or maintain the function in case of unpredictable risks or failures. The heterogeneous degree is on the opposite side, which defines the number of components, subsystems, or satellites performing different functions; namely degree of fractionation. In other words, fractionation describes the spatial distribution of the major functionalities of a space system. In the domain of time, the components, subsystems, or satellites to be designed and produced might be a derivative from previous ones in some ways, and such a heritage factor is defined as degree of derivation. A higher derivative degree generally implies a more mature design, or specifically, a more reliable system.

The detailed descriptions and formulation of the system characteristic space can be found in our previous research.[7]

4. Expected Launch Cost Analysis

Before performing the launch cost analysis, the launch vehicle database is established to provide the data for the modeling of launch reliability and cost. The launch reliability is modeled utilizing two levels of Bayesian analysis, while the cost is estimated for a dedicated launch. The estimate of launch reliability also influences the manufacturing cost, since launch failures might result in producing multiple copies of satellites. The reliability and cost information are later integrated into the expected launch cost, which shows the statistical expectation of the cost to ensure inserting a satellite into orbit at given confidence level. The expected launch cost can be used as an objective function for the optimization process associated with the manufacturing cost of satellites.

4.1. Launch data

For this research, the launch vehicle database established in our previous research[8] was updated to April 2018 based on online space launch reports.[9–11] The launch vehicle data is listed in Table 1 and Table 2 for active and retired vehicles, respectively. All of the launch vehicles are categorized into small (<5000 lb, <2268 kg), medium (<12000 lb, <5443 kg), intermediate (<25000 lb, <11340kg), and heavy (≥25000 lb, ≥11340 kg) classes, according to their launch capabilities in pounds to Low Earth Orbit (LEO).[12]

It is worth noting that the data of launch costs are the average costs of launch campaigns for each launch vehicle family. This may exclude the costs such as insurance and safety management. However, this is only a tiny proportion of the total launch costs, and therefore does not affect the significance of this study.

4.2. Bayesian analysis of launch reliability

In the database established, all of launch vehicles are categorized into different families. In each family, the launch vehicles are related and derivative to a great extent, due to the similar levels of individual technologies utilized. For those utilizing different or advanced technologies, a new family is generated, e.g., Atlas 400s and 500s. Thus, the record of launch history for different families of launch vehicles can be used to analyze their launch reliability.

Assuming the probability of successes of a launch vehicle family remains constant for every experiment, the space launch activities can be modeled as a series of Bernoulli trials[13] defined as random experiments with exactly two out-

Table 1. Launch data for active launch vehicle families.*

Launch vehicle family	Country	Mass class	Capability to LEO (kg)	Capability to GTO (kg)	Payload length (m)	Payload diameter (m)	Launch cost (FY2010$M)	Number of successes	Number of failures
Ariane 5G & 5E	Europe	Heavy	21000	6800	16.19	4.57	175.99	92	5
Atlas 5 401, 411, 421, 431	USA	Heavy	15700	7700	10.31	3.75	152.00	51	1
Atlas 5 501, 521, 531, 541, 551	USA	Heavy	20520	8900	12.92	4.57	172.50	23	0
Delta 2 6000 & 7000	USA	Medium	5144	1800	6.83	2.74	74.91	152	2
Delta 4M, 4M+, 4H	USA	Heavy	22560	13130	15.71	4.57	215.00	35	1
Dnepr	Russia	Medium	4400	0	4.20	2.70	20.43	21	1
Epsilon	Japan	Small	1200	0	5.39	2.12	38.00	3	0
Falcon 9 V1.0, 1.1, FT	USA	Heavy	22800	8300	11.00	4.60	56.22	45	3
Falcon Heavy	USA	Heavy	63800	26700	13.90	5.20	81.61	1	0
GSLV	India	Medium	5000	2350	7.30	3.05	44.00	6	5
H-2 & 2A	Japan	Heavy	11730	5000	10.23	3.70	101.25	41	3
H-2B	Japan	Heavy	16500	8000	9.12	4.60	142.42	6	0
Kosmos 3M	Russia	Small	1500	0	4.72	2.40	18.39	424	22
KZ	China	Small	300	0	1.40	1.20	2.61	3	0
Long March 2C & 2D	China	Medium	3500	1000	5.00	3.00	20.49	81	2
Long March 2E & 2F	China	Intermedium	8400	3500	6.54	3.80	68.10	18	2
Long March 3A & 3C	China	Intermedium	9100	3800	5.25	3.00	102.45	40	0
Long March 3B	China	Heavy	13600	5200	6.85	3.85	81.72	41	3
Long March 4A, 4B, 4C	China	Medium	4200	1500	6.50	3.35	47.81	50	2
Long March 5	China	Heavy	23000	13000	10.25	4.50	150.10	1	1
Long March 6	China	Small	1500	0	4.60	2.20	13.05	2	0
Long March 7	China	Heavy	13500	5500	6.85	3.80	87.45	2	0
Long March 11	China	Small	700	0	2.00	1.60	6.09	3	0
Minotaur I & IV	USA	Small	1735	0	5.71	2.04	45.96	17	0
Minotaur V	USA	Small	630	630	4.02	2.04	45.96	1	0
Pegasus & Pegasus XL	USA	Small	443	0	2.12	1.16	18.45	37	6
Proton K & M	Russia	Heavy	21000	5500	9.86	3.86	141.15	367	46
PSLV, PSLV-CA, PSLV-XL	India	Medium	3800	1300	5.40	2.90	20.11	39	3
Rockot	Russia	Small	1950	0	6.21	2.38	18.45	27	3
Shavit 1 & 2	Israel	Small	800	0	2.84	1.3	20.49	8	2
Shtil 1	Russia	Small	140	0	1.47	0.63	2.20	2	0
Soyuz 2.1	Russia	Intermedium	8200	3250	9.51	3.80	54.65	65	5
Soyuz U	Russia	Intermedium	7000	1660	9.00	2.85	54.65	764	21
Start-1	Russia	Small	632	0	2.31	1.24	12.29	6	0
Strela	Russia	Small	1560	0	2.95	2.20	14.34	3	0
Taurus & Taurus XL	USA	Small	1590	557	5.71	2.04	45.26	7	3
Vega	Europe	Small	1963	0	6.30	2.30	35.00	11	0
Volna	Russia	Small	140	0	1.25	0.82	1.57	2	3
Zenit 3 SL, SLB, SLBF	Russia	Heavy	15876	6066	8.53	3.75	115.77	42	4

*Small, medium, intermedium, and heavy launch vehicles are identified by their payload capabilities in kg to LEO (<2268, <5443, <11340, ≥11340).

Table 2. Launch data for retired launch vehicle families.

Launch vehicle family	Country	Mass class	Capability to LEO (kg)	Capability to GTO (kg)	Payload length (m)	Payload diameter (m)	Launch cost (FY2010$M)	Number of successes	Number of failures
Athena 1 & 2	USA	Small	2065	0	4.29	2.05	32.69	5	2
Ariane 4	Europe	Intermedium	10200	4790	11.12	3.65	153.23	113	3
Atlas 2, 2A, 2AS	USA	Intermedium	8618	3719	9.39	3.75	132.80	63	0
Atlas 3	USA	Intermedium	10759	4119	10.31	3.75	141.62	6	0
Cyclone 2 & 3	Russia	Medium	4100	0	6.60	2.40	28.28	219	9
Delta 2000	USA	Small	1860	724	4.93	2.18	57.90	43	1
Delta 3 8000	USA	Intermedium	8290	3810	9.93	3.75	122.94	1	2
Delta 3000, 4000, 5000	USA	Medium	3848	1405	6.12	2.54	67.85	38	3
Falcon 1	USA	Small	668	0	2.79	1.37	6.95	2	3
Long March 2A	China	Small	2000	0	5.00	3.00	28.80	3	1
Molniya-M	Russia	Medium	3700	0	4.04	2.35	47.81	276	21
M-V	Japan	Small	1900	1280	6.03	2.20	71.65	6	1
Soyuz	Russia	Intermedium	7000	1350	5.86	3.43	51.08	30	2
Space Shuttle	USA	Heavy	28803	5900	18.3	4.57	408.60	133	2
Titan 2	USA	Small	1900	0	6.65	2.83	47.81	13	0
Titan 3A & 3B	USA	Medium	3300	0	6.75	2.83	49.45	66	6
Titan 3C, 3D, 3E, 34D	USA	Heavy	14515	5000	8.27	2.83	250.93	71	9
Titan 4A & 4B	USA	Heavy	21600	5760	18.23	4.57	546.38	35	4
VLS-1	Brazil	Small	380	0	2.05	1.10	9.42	0	3
Zenit 2	Russia	Heavy	13740	0	12.24	3.40	57.89	30	8

comes: success or failure. Our work is to achieve the best estimate of this probability of success.

One of the biggest challenges in the modeling of space launch activities, distinguishing it from other Bernoulli trials such as coin-toss problems, is the limited sample size. This may increase the inaccuracy of the estimate. The Bayesian method is proposed to overcome this problem[14] as it incorporates prior knowledge of the known launch vehicles into the records of the observed launches of the launch vehicles in question, shown in Eq. (1).

$$f_{A|D}(a|s, f) = \frac{f_{D|A}(s, f|a) f_A(a)}{\int f_{D|A}(s, f|x) f_A(x) dx} \tag{1}$$

Where, A is the probability of successful launches given s successes and f failures in the past $t = s + f$ trials. The probability density function $f_A(a)$ is the prior distribution, representing the state of knowledge about a given launch vehicle prior to any of the t launch trials. The likelihood function $f_{D|A}(s, f|a)$ denotes the probability of the observed data D, namely, achieving s successes and f failures in t launch attempts. The result of the calculation $f_{A|D}(a|s, f)$ is the posterior distribution, which updates the previous knowledge with the realized launch data.

In previous research,[15] Howard derived a general form of Bayesian probability and demonstrated that the mean of the posterior distribution is the optimal estimate of the probability of successes. Based upon these mathematical fundamentals, Guikema and Pate-Cornell proposed using beta distribution as the conjugate prior distribution for modeling and analyzing the reliability of launch vehicles.[16]

$$f_A(a|s_0, f_0) = \frac{\Gamma(s_0 + f_0)}{\Gamma(s_0)\Gamma(f_0)} p^{s_0 - 1}(1 - p)^{f_0 - 1} \tag{2}$$

Where, $\Gamma(n)$ is the gamma function with parameter n.

$$\Gamma(n) = \int_0^\infty t^{n-1} e^{-t} dt \tag{3}$$

The mean and variance of the beta distribution can be presented by the parameters s and f.

$$\bar{p} = \frac{s}{s + f} \tag{4}$$

$$\sigma = \frac{sf}{(s + f)^2 (s + f + 1)} \tag{5}$$

If the updated observed data of s successes and f failures can be considered as the Bernoulli process, the posterior distribution is also a beta distribution with the parameters $s_0 + s$ and $f_0 + f$.

$$f_{A|D}(a|s, f) = \frac{\Gamma(s_0 + s + f_0 + f)}{\Gamma(s_0 + s)\Gamma(f_0 + f)} p^{s_0 + s - 1} \cdot (1 - p)^{f_0 + f - 1} \tag{6}$$

The two levels of Bayesian analysis proposed by Guikema and Pate-Cornell[16] are adopted in this paper for the reliability analysis of different types of launch vehicles. The first level applies the uniform distribution for the prior distribution of the Bayesian method. In this case, we assume that we know nothing about the reliability of these launch vehicles in advance. This level is appropriate for those launch vehicles with sufficient updating data, so that the prior distribution will have little influence on the posterior distribution, since the data dominates the updating process.

We fit the second-level prior distributions by combining the means of the first-level posterior distributions for all the launch vehicles except the one in question. This incorporates all of the experience of known launch vehicles. In this case, we assume that the probability of success for emerging launch vehicles is similar to previous ones, as much of the lessons learned in previous generations have been widely

Table 3. Means and variances of the posterior probability distribution function for active launch vehicle families.*

Launch vehicle family	Successes/Attempts	Successful rate (%)	First-level posterior		Second-level posterior	
			Means (%)	Variances (%)	Means (%)	Variances (%)
Ariane 5G & 5E	92/97	94.85	**93.94**	**0.06**	94.35	0.05
Atlas 5 401, 411, 421, 431	51/52	98.08	**96.30**	**0.06**	96.93	0.05
Atlas 5 501, 521, 531, 541, 551	23/23	100.00	**96.00**	**0.15**	97.35	0.09
Delta 2 6000 & 7000	152/154	98.70	**98.08**	**0.01**	98.28	0.01
Delta 4M, 4M+, 4H	35/36	97.22	**94.74**	**0.13**	95.72	0.10
Dnepr	21/22	95.45	**91.67**	**0.31**	93.44	0.23
Epsilon	3/3	100.00	80.00	2.67	**90.12**	**1.12**
Falcon 9 V1.0, 1.1, FT	45/48	93.75	**92.00**	**0.14**	92.87	0.12
Falcon Heavy	1/1	100.00	66.67	5.56	**86.29**	**1.98**
GSLV	6/11	54.55	53.85	1.78	**62.29**	**1.46**
H-2 & 2A	41/44	93.18	**91.30**	**0.17**	92.28	0.15
H-2B	6/6	100.00	87.50	1.22	**93.01**	**0.59**
Kosmos 3M	424/446	95.07	**94.87**	**0.01**	94.95	0.01
KZ	3/3	100.00	80.00	2.67	**90.12**	**1.12**
Long March 2C & 2D	81/83	97.59	**96.47**	**0.04**	96.88	0.03
Long March 2E & 2F	18/20	90.00	**86.36**	**0.51**	88.76	0.40
Long March 3A & 3C	40/40	100.00	**97.62**	**0.05**	98.36	0.04
Long March 3B	41/44	93.18	**91.30**	**0.17**	92.28	0.15
Long March 4A, 4B, 4C	50/52	96.15	**94.44**	**0.10**	95.16	0.08
Long March 5	1/2	50.00	50.00	5.00	**72.37**	**2.79**
Long March 6	2/2	100.00	75.00	3.75	**88.52**	**1.46**
Long March 7	2/2	100.00	75.00	3.75	**88.52**	**1.46**
Long March 11	3/3	100.00	80.00	2.67	**90.12**	**1.12**
Minotaur I & IV	17/17	100.00	94.74	0.25	**96.61**	**0.15**
Minotaur V	1/1	100.00	66.67	5.56	**86.29**	**1.98**
Pegasus & Pegasus XL	37/43	86.05	**84.44**	**0.29**	85.75	0.25
Proton K & M	367/413	88.86	**88.67**	**0.02**	88.80	0.02
PSLV, PSLV-CA, PSLV-XL	39/42	92.86	**90.91**	**0.18**	91.95	0.16
Rockot	27/30	90.00	**87.50**	**0.33**	89.12	0.28
Shavit 1 & 2	8/10	80.00	75.00	1.44	**80.76**	**1.04**
Shtil 1	2/2	100.00	75.00	3.75	**88.52**	**1.46**
Soyuz 2.1	65/70	92.86	**91.67**	**0.10**	92.29	0.09
Soyuz U	764/785	97.32	**97.20**	**0.00**	97.25	0.00
Start-1	6/6	100.00	87.50	1.22	**93.01**	**0.59**
Strela	3/3	100.00	80.00	2.67	**90.12**	**1.12**
Taurus & Taurus XL	7/10	70.00	66.67	1.71	**73.65**	**1.30**
Vega	11/11	100.00	92.31	0.51	**95.29**	**0.28**
Volna	2/5	40.00	42.86	3.06	**60.03**	**2.33**
Zenit 3 SL, SLB, SLBF	42/46	91.30	**89.58**	**0.19**	90.60	0.17

*The means and variances of the posterior probability to be used for each launch vehicle family are highlighted in bold.

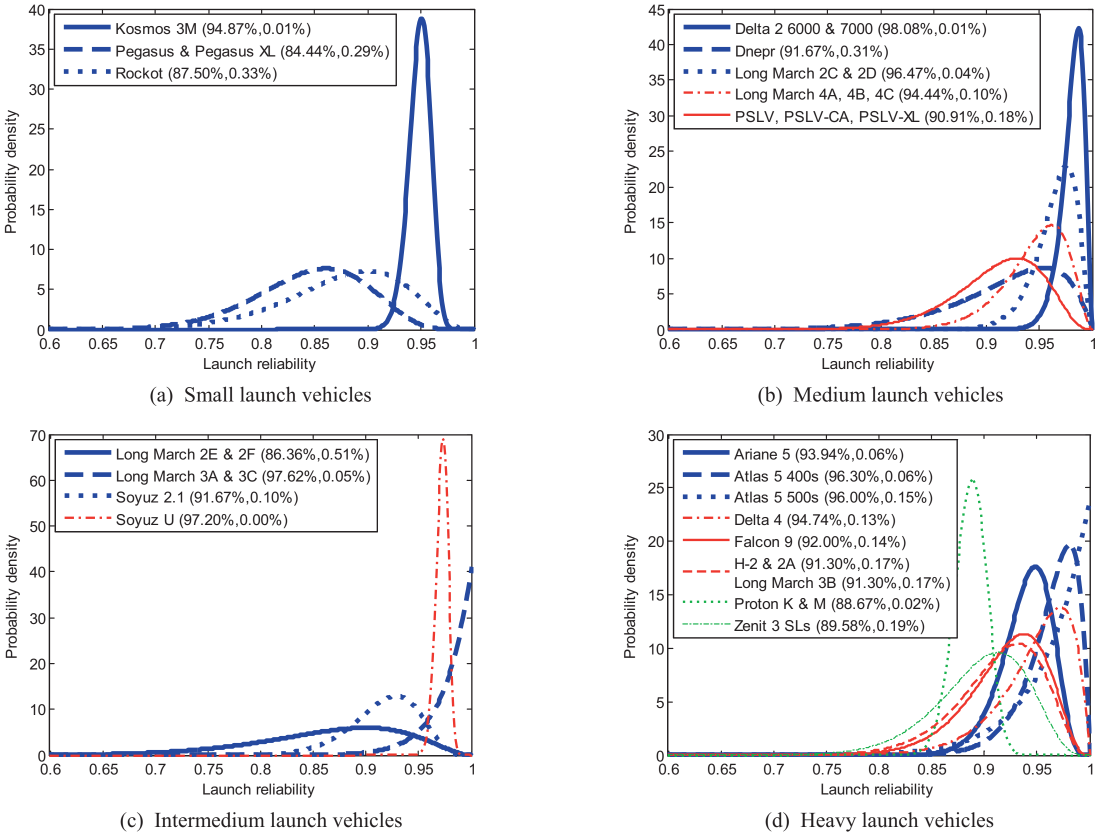
shared. The recorded data of all the other launch vehicles acts as the prior knowledge of launch activities, while the data of the launch vehicle to be investigated is used for the updating process. Therefore, this level of the Bayesian analysis can compensate for the lack of information about new launch vehicles or ones with limited launch trials. In addition, removing the information of the vehicle to be investigated in the prior distribution can solve the redundancy problem existing in the original second-level Bayesian analysis proposed by Guikema and Pate-Cornell.[16)]

The results of the two levels of Bayesian analysis for different launch vehicle families are summarized in Table 3, with the corresponding successful rates as the references. Overall, the Delta 2 family is the most reliable current launch vehicle, while the reliability estimate of the Soyuz U family exhibits the lowest uncertainty or variance as a result of the shear number of launches. Among the launch vehicles with limited trials, the Minotaur and Vega families have the highest expected reliability.

As stated above, different levels of reliability analysis are appropriate for different vehicles. In this research, we assume that the launch vehicles with at least 20 launches are considered to have comparatively sufficient updating data, thus are considered using only first-level analysis. On the contrary, the launch vehicles with less than 20 launches are classified as relatively novel or infrequently used, and considered using second-level analysis. Furthermore, the probability to be used for each launch vehicle family is highlighted in bold in Table 3.

Therefore, the posterior distributions of the Bayesian probability for different launch vehicle families are shown in Figs. 4 and 5, respectively. In both figures, the x-axis denotes the value of launch reliability and the y-axis shows the corresponding probability density.

As shown in Fig. 5, the absence of the intermedium class indicates that all of the active launch vehicles in this class are appropriate for first-level analysis. In other words, most novel launch vehicles are in the smaller classes, while the



(a) Small launch vehicles

(b) Medium launch vehicles

(c) Intermedium launch vehicles

(d) Heavy launch vehicles

Fig. 4. First-level posterior probability function for launch vehicles with at least 20 launch attempts.

other classes are mainly mature launch vehicles. Additionally, it is noteworthy that the launch vehicles lacking capability or cost information (e.g., SS-520) are not included here as additional information is necessary to enable use in launch cost analysis and optimization.

4.3. Expected launch cost

Expected launch cost refers to the statistical expectation of the cost of a successful launch; that is, successfully inserting the payload into an effective orbit, which is the combination of launch cost and launch reliability.

$$c_e = n_e \cdot c_l \tag{7}$$

Where, c_e denotes the proposed expected launch cost, c_l is the dedicated launch cost of a single launch attempt, and the number of statistical average launch attempts n_e to achieve a successful launch is defined by Eq. (8).

$$1 - (1 - r)^{n_e} \geq 1 - \alpha \tag{8}$$

Where, r is the reliability of the launch vehicle and α is the significant level or $1 - \alpha$ is the confidence level, a measure of how confident we want to be. Thus,

$$c_e \geq c_l \cdot \log_{1-r} \alpha \tag{9}$$

With the unit launch cost and reliability of different launch vehicles as the inputs, the expected launch cost can be obtained, taking α as 0.01. Therefore, the expected number of launch attempts and the corresponding cost of different launch vehicle families can be calculated utilizing Eq. (9) under a confidence level of 99%. The results are listed in Table 4. Utilizing this table, the optimal launch strategy can be looked up once the payload mass distribution is determined.

5. Optimization

To enable the optimization process of seeking an appropriate launch vehicle, the expected launch cost is used as the objective function associated with the development cost of the satellites to be launched. Having identified the problem as a mixed integer nonlinear programming (MINLP) problem, an appropriate optimization algorithm is adopted. Three classical launch cases are reviewed and redesigned to show the effectiveness and applicability of the method proposed.

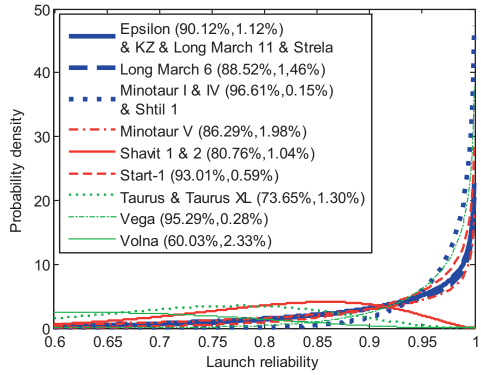
5.1. Optimization techniques

The optimization process for space system launch cost can be mathematically summarized as a MINLP problem, Eq. (10).

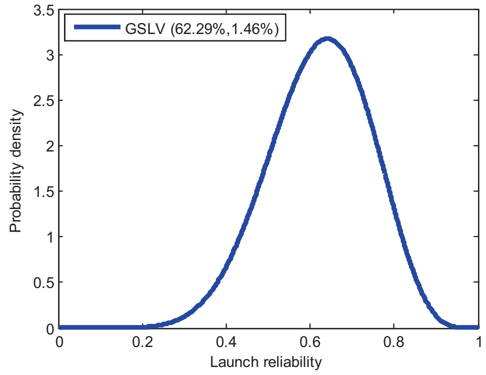
$$\begin{aligned} &\min \quad J(x) \\ &\text{s.t.} \quad x_j^l \leq x_j \leq x_j^u\text{: integer} \quad j = 1, 2, \cdots, n \\ &\qquad x = [x_1 \quad x_2 \quad \cdots \quad x_n]^{\mathrm{T}} \end{aligned} \tag{10}$$

Where, $J(x)$ is the objective function, n is the number of state variables, x_j is the state variable, and x_i^l and x_i^u are the corresponding lower and upper bounds, respectively.

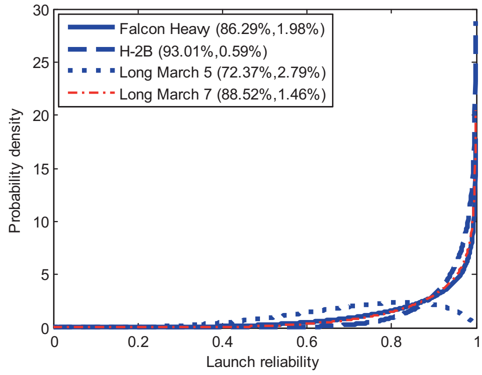
More specifically, the objective function $J(x)$ is the launch cost under riskin this research, which will be described in detail. The state variable x is the System Sequence Vector pro-



(a) Small launch vehicles



(b) Medium launch vehicles



(c) Heavy launch vehicles

Fig. 5. Second-level posterior probability function for launch vehicles with less than 20 launch attempts.

Table 4. Expected number of launches required to get a 99% confidence in deploying necessary satellites in orbit and the corresponding cost for active launch vehicle families.

Launch vehicle family	Expected launches	Expected cost (FY2010$M)
Ariane 5G & 5E	1.64	289.10
Atlas 5 401, 411, 421, 431	1.40	212.38
Atlas 5 501, 521, 531, 541, 551	1.43	246.79
Delta 2 6000 & 7000	1.17	87.31
Delta 4M, 4M+, 4H	1.56	336.26
Dnepr	1.85	37.86
Epsilon	2.55	96.82
Falcon 9 V1.0, 1.1, FT	1.82	102.51
Falcon Heavy	3.38	275.62
GSLV	5.52	242.72
H-2 & 2A	1.89	190.91
H-2B	2.07	295.15
Kosmos 3M	1.55	28.52
KZ	2.50	6.52
Long March 2C & 2D	1.38	28.22
Long March 2E & 2F	2.31	157.40
Long March 3A & 3C	1.23	126.23
Long March 3B	1.89	154.09
Long March 4A, 4B, 4C	1.59	76.17
Long March 5	5.22	783.13
Long March 6	2.84	37.00
Long March 7	2.87	251.13
Long March 11	2.50	15.25
Minotaur I & IV	1.49	68.58
Minotaur V	3.37	154.98
Pegasus & Pegasus XL	2.47	45.66
Proton K & M	2.11	298.43
PSLV, PSLV-CA, PSLV-XL	1.92	38.62
Rockot	2.21	40.86
Shavit 1 & 2	3.13	64.18
Shtil 1	2.80	6.16
Soyuz 2.1	1.85	101.28
Soyuz U	1.29	70.35
Start-1	2.03	24.95
Strela	2.52	36.20
Taurus & Taurus XL	3.93	177.96
Vega	1.69	59.32
Volna	6.87	10.78
Zenit 3 SL, SLB, SLBF	2.04	235.72

posed in our previous research.[7] It is used to define the combinations and permutations of a space system (e.g., a constellation of identical spacecraft or a fractionated spacecraft) when considering duplication and/or fractionation. As the elements of the System Sequence Vector are all integers,[7] this optimization can be included in the MINLP problem.

Since MINLP problems have been widely discussed in previous studies, one of the recent findings is adopted here, namely, the genetic algorithm (GA) associated with Laplace Crossover (LX),[17] Power Mutation (PM),[18] and a truncation technique, which is called the MI-LXPM algorithm by Deep et al.[19]

5.2. Objective function

Adopting the expected launch cost as the objective function for the optimization process is one of the simplest solutions. However, if the design and development cost of space systems is not taken into account, the optimization process is likely to distort the facts. In order to distinguish different risk control requirements, the development and deployment cost is adopted as the objective function of the optimization process, including both the expected launch cost and the cost of the satellites to be launched. Thus,

$$c_d = (c_l + c_s) \cdot \log_{1-r} \alpha \tag{11}$$

where, c_d is the expected development and deployment cost, and c_s is the cost of the launched satellites.

A learning curve is used to predict the average unit cost of the launched satellites when more than one identical or near identical satellites is produced.

$$c_a = c_{T1} \cdot n_l^{\ln(l)/\ln(2)} \tag{12}$$

Where, c_a is the average unit cost, c_{T1} is the theoretical first unit production cost, n_l is the number of units being built at the same time, and l is the learning curve slope. In the aerospace industry, l is typically 95%.

Table 5. Cases of dedicated launch cost optimization.

Mission	Actual cost (FY2010$M)	Expected cost of actual launch vehicle (FY2010$M)	Optimized expected cost (FY2010$M)
HST	408.6	492.4	336.3
Galileo	569.0	854.4	478.0
Flock 3p	~10.0	35.4*	28.22

*This cost is estimated based on the dedicated launches under risks, while the cost of the piggyback launch that was actually used is given in the actual cost column.

Table 6. Optimal dedicated launch strategies for each case.

Mission	Expected launch vehicles	Launch attempts	Number of satellites per launch
HST	Delta 4M, 4M+, 4H	1	1
Galileo	Soyuz U	5	2
	Long March 3A & 3C	1	4
Flock 3p	Long March 2C & 2D	1	88

5.3. Discussions about optimization results

The typical launch cases of space systems are reviewed and redesigned by the approach proposed. The results are shown in Table 5 with the specific launch strategies exhibited in Table 6.

The first case is a monolithic spacecraft, the largest and most powerful on-orbit telescope, the Hubble Space Telescope (HST).[20] HST weighted 11,866 kg, and its development cost was over $1,500 M in fiscal year 2010.[21] It was deployed by the Space Shuttle Discovery on April 24, 1990, at an estimated launch cost of more than $400 M.[12]

In this case, any launch failure is intolerable since the development cost of the satellite is far more expensive than the launch cost. The risk level of this launch mission needs to be controlled to be as low as possible. Thus, more reliable launch vehicles with adequate launch capability are more appealing. If this mission was implemented by currently available launch vehicles, the Delta 4 would probably be the best solution since the Space Shuttle has been retired.

The second case exhibits the launch strategy optimization of a constellation such as the European Global Navigation Satellite System (GNSS) Galileo. The full operational capability (FOC) of Galileo consists of 14 identical navigation satellites each weighing 733 kg,[22] which were launched in six independent launch missions (i.e., the former five missions launched two satellites and the last one launched four satellites). Due to different orbit requirements and manufacturing time, the launch sequence is retained in this case. Therefore, only the launch strategy for each mission is optimized.

The results of this case reveal that the launch missions of Galileo FOC are well-organized, and the optimal strategy only saves 16.0% of the original cost.

The last is a small satellite constellation case. Flock 3p is a constellation with 88 cubesats each weighting 4.7 kg.[23] The mission was performed by PSLV-XL on February 15, 2017,[24] which launched a record 104 satellites in a single launch attempt.

The reason for the reduction of the launch cost for Flock 3p is that the constellation is the secondary payload of this launch mission. However, the objective of the approach proposed is finding a better dedicated launch strategy. The result shows that the optimal solution saves 20% of the expected launch cost, but still costs more than the actual mission. This proves the advisability and advantage of rideshare or piggyback launches.

Such a result may have two implications for the space launch market. On one hand, current dedicated launches are not economically comparable to rideshare or piggyback launches in the small satellite market. On the other hand, innovative launch vehicles need to be developed, especially for the small satellite market.

6. Conclusions

This research focused on developing a methodology for analyzing and optimizing the dedicated launch cost of different space systems under a value-centric design architecture based on the system characteristic space.

The system characteristic space, consisting of duplication, fractionation, and derivation, is firstly introduced as the design space for analyzing the launch cost. The different designs of a space system can be defined in this space, which enables the integration process of the mass property from the subsystem level into the system level.

Subsequently, system mass property is converted into the launch cost. More specifically, the expected launch cost is adopted as the measurement of system value, which synthesizes the factors of both launch reliability and launch cost. The reliability of different launch vehicles is calculated utilizing a modified two-level Bayesian analysis. The first level is applied for mature launch vehicles with at least 20 launch attempts, while the second level is appropriate for launch vehicles still in the infant phase (e.g., less than 20 launch attempts).

Based upon our launch vehicle database, a value model is established where the expected launch costs of various families of launch vehicles are defined, calculated, and compared under a 99% confidence level. In order to control the launch risks, the development cost of a space system is introduced to comprise the expected development and deployment cost associated with the expected launch cost. This value is used as the objective function to enable the loop of value flow in the entire architecture.

Having identified the problem proposed as a MINLP problem, an appropriate optimization algorithm is found to reach the solution with the minimum expected launch cost. Three typical cases were investigated and reviewed, and the results validated the effectiveness and the applicability of the value-centric design approach proposed.

Acknowledgments

The authors gratefully thank the financial support from the China Scholarship Council (CSC) (201403170413) for this work.

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