

Economic Evaluation of Mission Architecture for Cislunar and beyond Utilizing Orbital Transfer Vehicle

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This paper proposes a method to evaluate the economic efficiency of transportation by orbital transfer vehicles (OTV). In previous studies, transportation efficiency has been evaluated based on future technologies, such as the reusability of OTVs in orbit and assuming ISRU on the lunar surface. However, the economic and business feasibility of disposable OTVs in the process leading up to these technologies has not been fully evaluated. Therefore, this study quantitatively shows that a general-purpose OTV can be used for transportation to various orbits, such as geostationary, lunar, and Mars, and that even disposable OTVs have high economic efficiency. We formulate problems that span multiple domains, such as OTV subsystems and costs, as a multidisciplinary system design optimization problem, propose a method to solve the problem as a multi-objective optimization problem, and provide guidelines for OTV design and a comparison of economic efficiency with and without OTV.

Key Words: Space Logistics, Multidisciplinary System Design Optimization

Nomenclature

M_{total}	: total wet mass, kg
M_{launch}	: launch mass, kg
M_{prop}	: propulsion mass, kg
M_{tank}	: tank mass, kg
M_{ptank}	: pressurant tank mass, kg
$M_{thruster}$	: thruster mass, kg
M_{pipe}	: piping mass, kg
M_p	: propellant mass, kg
p_{MEOP}	: tank pressure, Pa
D	: diameter of tank, m
L	: length of tank, m
SF	: safety rate
MR	: mixing ratio
ρ	: density of tank, kg/m ³
ρ_f	: density of MMH, kg/m ³
I_{sp}	: specific impulse, s
ΔV	: velocity change, m/s
M_{pay}	: payload mass, kg
M_{avi}	: avionics mass, kg
W	: weighting factor

Subscripts

LEO	: Low Earth Orbit
GTO	: Geostationary Transfer Orbit
GEO	: Geostationary Earth Orbit
LTO	: Lunar Transfer Orbit
EMT	: Earth-Mars Transfer Trajectory
NRHO	: Near-recliner Halo Orbit
ELFO	: Elliptical Lunar Frozen Orbit
LLO	: Low Lunar Orbit
EMO	: Elliptic Mars Orbit

1. Introduction

Last mile services, in which a ride-shared satellite is delivered to the user's desired orbit by a spacecraft called an orbital transfer vehicle (OTV) or space tug, are gaining momentum around the world. There are 15 companies offering last mile services, including those aiming to be in service by FY2025. Most of these companies have already demonstrated their services in low earth orbit, while few have demonstrated their services in geostationary orbit or beyond cislunar orbit.

Therefore, it is important for Japan, which has experience of rendezvous docking with HTV and of deep space proximity operations with Hayabusa2 mission, to promote the development of OTVs for geostationary and beyond lunar orbit, which is still a blue ocean. This policy is also described in the Space Technology Strategy for 2025, and development and demonstration of OTV are proposed as one theme of the second phase of space strategy fund¹⁾. Thus, this study deals with the economics of space logistics by OTV, the design of OTV with business potential, and mission architecture, which are still insufficiently studied.

In the past, Nakasuka et al. evaluated the economics of OTV network in which OTVs are reused for space transportation²⁾. Ishimatsu and Ho et al. proposed a method to optimize a complex mission by considering the circulation of materials in space by plants on the lunar surface in addition to OTVs^{3,4)}. However, these studies assume a large-scale infrastructure such as a huge orbital depot and ISRU on the lunar surface, and it will take time to reach such a future. In addition, there is insufficient quantitative evaluation of the economic feasibility of OTVs in the transitional state leading up to that future. Furthermore, there is no established means of solving the problem of the close intertwining of OTV business feasibility

and the spacecraft's design.

We have proposed a feasible on-orbit reuse strategy in which the fuel tank module is launched every time the OTV for lunar transportation receives propellant refueling. And, we have also developed a method to evaluate the feasibility and the efficiency of reusable OTVs' transportation by solving a multidisciplinary system optimization problem that covers mission scenarios, orbits, OTV subsystems and costs^{5,6)}. However, there has been no study of the design and economic and business feasibility of OTVs when they are operated on a disposable basis prior to on-orbit reuse or when versatile OTVs are applied to geostationary orbit, cislunar, and deep-space transportation.

In this paper, we propose a method to evaluate the economic efficiency and business feasibility of a versatile OTV for OTV's business in the near future by expanding the target trajectory of OTV service, and by expanding the optimization from single-objective optimization to multi-objective optimization, after refining each subsystem model in the previous multidisciplinary system optimization. A methodology is proposed and demonstrated through numerical analysis.

2. Graph and adjacency matrix

This section defines the start orbit, rocket separation, and the target orbit to which OTV delivers the user's satellite covered in this study as a graph. This study focuses on near-earth orbits to cis-lunar orbits and Martian orbit as shown in Fig. 1. As near-earth orbits, low earth orbit (LEO), geostationary transfer orbit (GTO), and geostationary orbit (GEO) are considered. As lunar orbits, Near-recliner Halo Orbit (NRHO) that will be utilized for gateway, Elliptical Lunar Frozen Orbit (ELFO) that is convenient for the satellite of lunar navigation satellite system, and low lunar orbit (LLO) that is essential for observation of the surface are taken into account. The user's satellite is inserted into these lunar orbits via lunar transfer orbit (LTO). In addition, it is considered that OTV delivers the satellite to elliptic Mars orbit (EMO) via Earth-Mars transfer trajectory.

The required ΔV for transferring between each orbit can be expressed by an adjacency matrix of the graph as shown in Fig. 2⁷⁻⁹⁾. Note that this paper does not consider the round-trip trajectory from cis-lunar or Martian to near-earth orbit because of focusing on the disposable OTV.

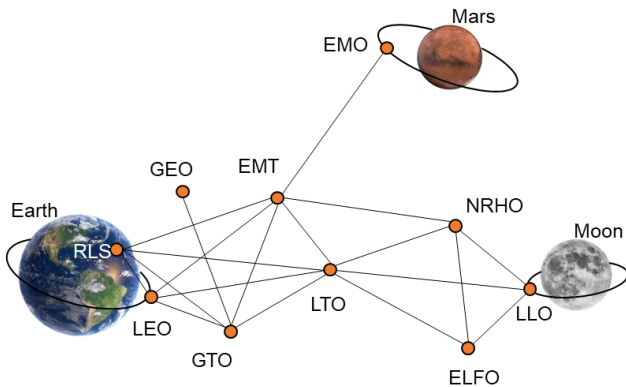


Fig. 1. Start orbits and target orbits of OTV service illustrated as a graph.

		To									
From	LEO	GTO	GEO	LTO	EMT	NRHO	ELFO	LLO	EMO		
			2.4		3.02	3.12					
	GTO			1.85	0.68	0.77					
	GEO										
	LTO						0.4	0.6	0.83		
	EMT									2	
	NRHO							0.55	0.65		
	ELFO						0.55	0.1	0.8		
	LLO						0.65	0.8			
	EMO										

Fig. 2. ΔV s (km/s) between each node as an adjacency matrix.

3. Flow of algorithm

The flow of the algorithm for evaluating the economic efficiency of OTV is expressed as follows:

1. Generate a graph
2. Search all paths
3. Select paths for optimization
4. Multidisciplinary System Design Optimization
5. Select the decision parameters from pareto front
6. Evaluate economic efficiency of all paths

First of all, a graph is generated that is explained in Sec.2. In the second step, regarding all combinations of start nodes and target nodes, the shortest paths are searched by Dijkstra's algorithms. And, after selecting paths for optimization, multidisciplinary system design optimization is executed. In Sec.5, a case study selecting GTO-GEO, LTO-LLO, and EMT-EMO will be explained. Step 4 is described in the next section and 5 and 6 are described in Sec.5 with concrete case study.

4. Multidisciplinary System Design Optimization

The problem that involves multiple domains are solved by multidisciplinary system design optimization (MSDO). Figure. 3 shows the block diagram of multidisciplinary system design optimization and Table.1 shows the variables, objective function, and constraint of optimization. M_p , M_{st} , M_{pay} , $M_{p,req}$, RC, and N indicate mounted propellant masses for each selected paths, structure mass of OTV, payload mass, required propellant masses for each selected paths, recurring cost, and the number of selected paths. Two objectives are considered. The first objective is maximizing the average payload mass, and the second objective is minimizing the average of cost per payload mass. The second objective J_2 is expected to be the indication of versatility of OTV for various target orbits because J_2 acts to balance the cost per payload mass for selected paths. Each subsystem model is explained in the next subsections.

Table 1. Variables, objective function, and constraint of optimization.

Variables	- M_p
	- M_{st}
Objective function	- $J_1 = \frac{1}{N} \sum_i^N -M_{pay,i}$
	- $J_2 = \frac{1}{N} \sum_i^N \frac{RC_i}{M_{pay,i}}$
Constraint	- $M_{p,req} = M_p$

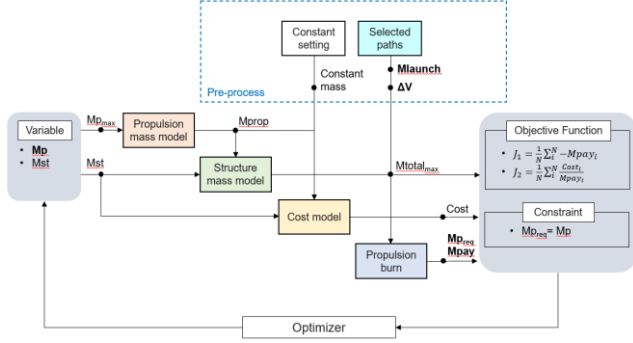


Fig. 3. Block diagram of multidisciplinary system design optimization.

4.1. Launch condition

Assuming the launch capability curve of the H3 rocket, the launch mass is obtained as a function of the launch energy C3 as in equation (1).

$$M_{launch} = f(C_3) \quad (1)$$

While equation (1) indicates the single launch case, launch mass of the dual launch case is calculated as follows:

$$M_{launch} = \frac{f(C_3) - M_{dispenser}}{2} \quad (2)$$

Mass of the dispenser $M_{dispenser}$ is subtracted from the launch capability curve.

4.2. Propulsion model

Propulsion mass model is described in this subsection. MMH/MON3 bipropellant propulsion system is considered. Propulsion mass can be expressed by Eq. (3).

$$M_{prep} = M_{tank} + M_{ptank} + M_{thrust} + M_{pipe} \quad (3)$$

where tank mass M_{tank} and pressurant tank mass M_{ptank} are variables of the max capacity of propellant and thruster mass and piping mass are set to be constant values. The cylindrical shape of tank is considered and tank mass is expressed as follows:

$$t_{hemi} = \frac{p_{MEOP} \cdot D \cdot SF}{4\sigma}, \quad t_{cyl} = \frac{p_{MEOP} \cdot D \cdot SF}{2\sigma} \quad (4)$$

$$V = \frac{M}{(1+MR)\rho_f A} \quad (5)$$

$$L = \frac{4V}{\pi D^2} + \frac{D}{3} \quad (6)$$

$$M_{tank} = (\pi D^2 \cdot t_{hemi} + \pi D(L - D))\rho \quad (7)$$

where t_{hemi} , t_{cyl} , p_{MEOP} , D , L , V , SF , σ , ρ , ρ_f , M , MR , and A are thickness of hemisphere part and cylindrical part of tank, tank pressure, diameter of tank, length of tank, volume of tank,

safety rate, strength of tank, density of tank, mass of propellant, mixing ratio, density of MMH, and filling rate. The mass of tank can be obtained as the function of the mass of propellant by substituting eq. (4-6) to (7). It was found that the pressurant tank mass can be estimated by Eq. (8) by the previous work¹⁰.

$$M_{ptank} = \frac{p_i V_{ptank}}{g \cdot \phi_{ptank}} \quad (8)$$

where p_i , V_{ptank} , ϕ_{ptank} are initial gas pressure, the volume of pressurant tank, and tank mass factor respectively. Thus, propulsion mass can be calculated as the function of the propellant mass.

4.3. Structure model

Structure efficiency is defined as structure mass divided by wet mass as shown in Eq. (9).

$$\beta = \frac{M_{st}}{M_{total,max}} \quad (9)$$

The structure efficiency of 18 JAXA's previous satellites are investigated and shown in Fig.4. The structure model is obtained by approximation of the relation of wet mass and structure efficiency. The maximum of wet mass $M_{total,max}$ is obtained by the structure mass and Eq. (9). The actual wet mass M_{total} is calculated as the smaller of $M_{total,max}$ and launch mass.

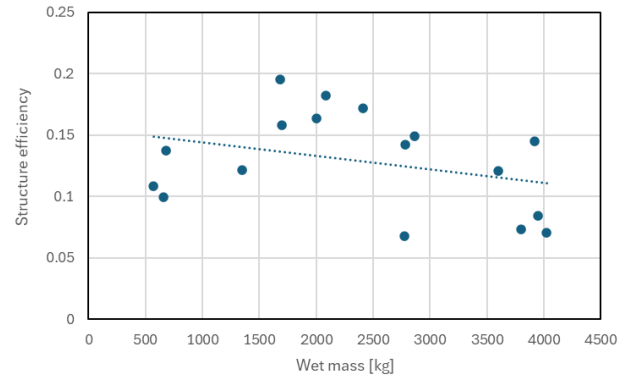


Fig. 4. Structure efficiency of JAXA's previous satellites

4.4. Propulsion burn

The required propellant masses for each path can be obtained corresponding to the required ΔV for selected paths by the rocket equation.

$$M_{p,req} = M_{total} \left(1 - \exp \left(-\frac{\Delta V}{g I_{sp}} \right) \right) \quad (10)$$

This required propellant mass is used for constraint shown in Table.1. The payload masses for each target orbit can be obtained by Eq. (11).

$$M_{pay} = M_{total} - M_{avi} - M_{str} - M_{prop} - M_p \quad (11)$$

4.5. Cost

Cost estimation also plays a key role for evaluating OTV's performance as cost per mass of transportation. This study applied the cost model estimated by mass of each subsystem, power consumption, volume, and the number of thrusters⁹.

Table. 2 indicates the formulation of each cost of the spacecraft, integration, assembly & test, and program level. Cost can be divided into non-recurring cost (NRC) for research, development, test, and environment and recurring cost (RC) for manufacturing. When cost per payload mass for the second objective function, only RC is considered for simplicity.

Table 2. Cost calculation table.

Items		Research, Development, Test, and Environment (Non-Recurring) [S]	Theoretical First Unit (Recurring) [S]
Spacecraft	Structure	$157M_{str}^{0.83}$	$13.1M_{str}^{0.83}$
	EPS	$2.63(M_{eps}P_t)^{0.712}$	$112M_{eps}^{0.763}$
	TTC-DH	$545M_{ttc-dh}^{0.761}$	$635M_{ttc-dh}^{0.568}$
	AOCS	$464M_{aocs}^{0.867}$	$293M_{aocs}^{0.777}$
	Thermal	$1.1M_{thrm}^{0.61}M_{dry}^{0.943}$	$50.6M_{thrm}^{0.707}$
	Propulsion	$(65.6 + 2.19M_{dry}^{1.261} + 1539 + 434 \log V_{bus} + 4303 - 3903N_{tn}^{-0.5}) \cdot 2/3$	$0.5(\text{Cost of RDT\&E})$
Sub total		Sum of spacecraft's RDT&E	-
IA&T		$989 + 0.215(\text{Cost of RDT\&E})$	$10.4M_{dry}$
Program level		$1.963(\text{Cost of RDT\&E})^{0.841}$	$0.314(\text{Cost of RDT\&E})$

5. Result of a case study

This section describes the result of MSDO and evaluation of economic efficiency with it. This case study selected the following three paths for optimization.

- Path1: GTO-GEO
- Path2: LTO-LLO
- Path3: EMT-EMO

Disposable but commonly designed OTV covers the transportations from geostationary to cis-lunar and Mars. The calculation condition of multi-objective optimization by genetic algorithms is shown in Table. 3.

Table 3. Calculation condition of optimization.

Items	Value
Variables	M_{st} [360 kg, 564 kg] $M_{p,i} \forall i \in \{1,2,3\}$ [0 kg, 2500 kg]
Population size	200
Maximum of generation	500

5.1. Pareto solution

Solution space is illustrated in Fig.5. Figure.5 includes dominated solutions and pareto solutions against two objective functions J_1 and J_2 . It is found that the average of payload mass and the average of cost per payload mass for GEO, LLO, and EMO have trade-off relation. The edges of pareto solutions are picked up and shown in Table.4 and Table.5. Table.4 indicates optimized performance of OTV and Table. 5 shows optimized decision parameters. Table.4 reveals that the payload masses for GEO and LLO become large and that of EMO become small in case 2 so that J_1 becomes larger. On the other hand, the average cost per payload mass, J_2 also becomes large in case 2 compared to case 1 because the payload mass for EMO of case 2 is smaller than that of case 1. The optimized decision parameters in Table.5 reveal that structure mass and wet mass of case 1 are approximately minimum and those of case 2 are approximately maximum. On the other hand, there is little

difference in the propulsion masses of case 1 and case 2 because the maximum propellant of case 1 and case 2 are almost same. Therefore, these results indicate that if the structure of OTV is designed to be large in order to endure the large wet mass for the maximum rocket launch capability to near-earth orbit, the overall payload mass can be maximized, while the payload for high energy orbit such as beyond cis-lunar becomes smaller and the balance of cost per mass for various target orbits becomes inferior.

In order to give the policy to determine the OTV design, the third objective function J_3 is introduced. J_3 is the average cost per mass weighted by weighting factors as expressed by Eq. (12).

$$J_3 = \frac{1}{N} \sum_i^N W_i \frac{RC_i}{M_{pay,i}} \quad (12)$$

The number of satellites launched to GEO, cis-lunar, and Mars are predicted to be around 18, 5, and 1.5 per year in 2030 by the reference [11]. The ratio of these numbers can derive weighting factors as case A in Table.6. Case B is that the number for GEO will be reduced to 20 % and that of LLO and EMO increases 10 % respectively. The pareto solution colored by case A and B of J_3 are shown in Fig. 6 and 7. It is found that the best design, the minimum of weighted cost per payload mass varies depending on weighting factors. This indication based on the transportation demand market forecast is useful to determine the design parameters of OTV. Figure. 9 shows the relations between the payload mass and usage cost.

Table 4. Optimized performance.

Items	Case 1	Case 2
J_1	1051.4 [kg]	1394.6 [kg]
J_2	13.6 [million yen/kg]	19.5 [million yen/kg]
M_{pay} for GEO	1086 kg	1843 kg
M_{pay} for LLO	1562 kg	2038 kg
M_{pay} for EMO	506.5 kg	303.3 kg
RC	11571 [million yen/kg]	13516 [million yen/kg]

Table 5. Optimized decision parameters.

Items	Case1	Case2
M_{st}	372.0 kg	563.9 kg
M_{prop}	184.3 kg	195.5 kg
M_p for GEO	1239 kg	1878 kg
M_p for LLO	762.5 kg	983.9 kg
M_p for EMO	1718 kg	1718 kg
M_{total} for GEO	3099 kg	4699 kg
M_{total} for LLO	3099 kg	4000 kg
M_{total} for EMO	3000 kg	3000 kg

Table 6. Weighting factor.

Weighting factor	Case A	Case B
W_{GEO}	0.74	0.54
W_{LLO}	0.20	0.30
W_{EMO}	0.06	0.16

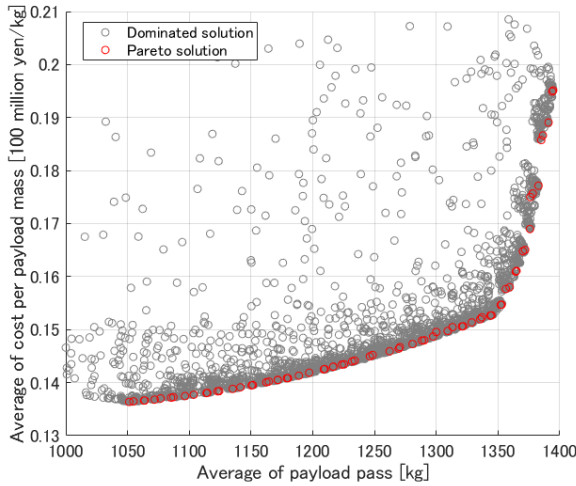
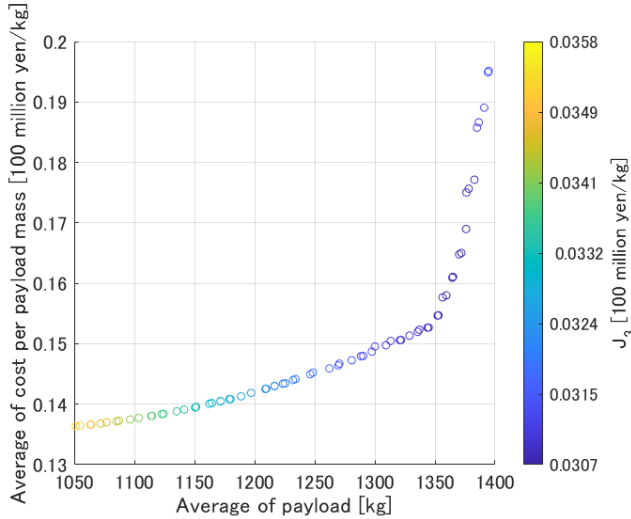
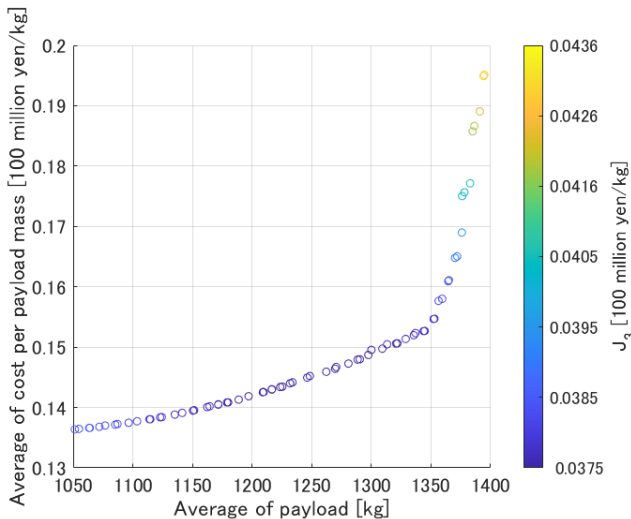


Fig. 5. Pareto solution and dominated solution.

Fig. 6. Pareto solution colored by J_3 (case A).Fig. 7. Pareto solution colored by J_3 (case B).

5.2. OTV service catalog

Along with the flow of the algorithm for evaluating the economic efficiency of OTV explained in Sec.3, this subsection describes the result of step 6. After the OTV's design parameters are fixed, payload and cost performance to all paths are evaluated and the result is obtained as an OTV service catalogue as shown in Fig.8. Referring Fig.8, when the users choose rocket, launch type, the number of target orbits, the number of payloads, and target orbit, they can get the payload mass capability and its cost. The cost per mass is sorted in ascending order and there are no cases where the OTV is separated in LEO because those are infeasible for much delta-V requirement. The cross plots indicate the single payload mounted on OTV by single launch and the circle plots indicate the multiple payloads on OTV and/or by dual launch. It is important that a unique delivery by OTV, multiple payloads can reduce the usage cost per one user instead that the payload mass per one user is also reduced.

ID	Rocket	Launch type	The number of target	The number of payloads per an orbit	Rocket separation trajectory	Target orbit 1	target orbit 2	Payload mass 1	Payload mass 2	Usage cost [100 million yen]	Cost per mass [100 million yen/kg]
11H3-225	Single	1	1	1	1	NRHO	-	2225.763	-	170	0.076243
20H3-225	Single	1	1	1	1	NRHO	-	1114.9015	-	85	0.056601
12H3-225	Single	1	1	1	1	ELFO	-	2028.8653	-	170	0.083779
28H3-225	Single	1	1	1	1	ELFO	-	1014.4427	-	85	0.083779
41H3-225	Single	1	1	1	1	NRHO	ELFO	933.9664	933.9664	85	0.091001
59H3-225	Single	1	1	1	1	NRHO	ELFO	466.9632	466.9632	42.5	0.091001
13H3-225	Single	1	1	1	1	LLO	-	1814.1319	-	170	0.093709
27H3-225	Single	1	1	1	1	LLO	-	907.06596	-	85	0.093709
40H3-225	Single	1	1	1	1	LLO	LLO	901.3169	901.3169	85	0.094306
60H3-225	Single	1	1	1	1	NRHO	LLO	450.6585	450.6585	42.5	0.094306
43H3-225	Single	1	1	1	1	ELFO	NRHO	842.886	842.886	85	0.10084
63H3-225	Single	1	1	1	1	ELFO	NRHO	421.443	421.443	42.5	0.10084
70H3-225	Single	1	1	1	1	ELFO	-	1598.9526	-	170	0.10632
23H3-225	Single	1	1	1	1	NRHO	-	799.49632	-	85	0.10632
44H3-225	Single	1	1	1	1	ELFO	LLO	765.7112	765.7112	85	0.11101
64H3-225	Single	1	1	1	1	ELFO	LLO	382.8556	382.8556	42.5	0.11101
71H3-225	Single	1	1	1	1	ELFO	-	1429.7369	-	170	0.11809
25H3-225	Single	1	1	1	1	NRHO	-	719.78944	-	85	0.11809
45H3-225	Single	1	1	1	1	LLO	NRHO	716.3722	716.3722	85	0.11809
65H3-225	Single	1	1	1	1	LLO	NRHO	358.1861	358.1861	42.5	0.11809
46H3-225	Single	1	1	1	1	LLO	ELFO	652.107	652.107	85	0.13035
66H3-225	Single	1	1	1	1	LLO	ELFO	326.0535	326.0535	42.5	0.13035
30H3-225	Single	1	1	1	1	NRHO	ELFO	596.7634	596.7634	85	0.14244
53H3-225	Single	1	1	1	1	NRHO	ELFO	298.387	298.387	42.5	0.14244
72H3-225	Single	1	1	1	1	ELFO	-	1157.6692	-	170	0.14685
26H3-225	Single	1	1	1	1	ELFO	-	578.83487	-	85	0.14685
89H3-225	Single	1	1	1	1	LLO	-	1143.1405	-	170	0.14871
24H3-225	Single	1	1	1	1	LLO	-	571.57068	-	85	0.14871
73H3-225	Single	1	1	1	1	NRHO	-	912.9515	-	140	0.15344
88H3-225	Single	1	1	1	1	NRHO	-	458.1957	-	70	0.15344
36H3-225	Single	1	1	1	1	NRHO	LLO	539.2683	539.2683	85	0.15762
54H3-225	Single	1	1	1	1	NRHO	LLO	269.6341	269.6341	42.5	0.15762
74H3-225	Single	1	1	1	1	ELFO	-	811.2427	-	140	0.17243
90H3-225	Single	1	1	1	1	ELFO	-	405.6713	-	70	0.17243
75H3-225	Single	1	1	1	1	NRHO	-	797.3954	-	140	0.17557
80H3-225	Single	1	1	1	1	NRHO	-	398.6978	-	70	0.17557
37H3-225	Single	1	1	1	1	ELFO	NRHO	455.7719	455.7719	85	0.1860
56H3-225	Single	1	1	1	1	ELFO	NRHO	227.886	227.886	42.5	0.1860
100H3-225	Single	1	1	1	1	NRHO	ELFO	356.2901	356.2901	70	0.19647
121H3-225	Single	1	1	1	1	NRHO	ELFO	178.145	178.145	35	0.19647
77H3-225	Single	1	1	1	1	LLO	-	704.566	-	140	0.1987
91H3-225	Single	1	1	1	1	LLO	-	352.283	-	70	0.1987
76H3-225	Single	1	1	1	1	ELFO	-	701.7473	-	140	0.1995
81H3-225	Single	1	1	1	1	ELFO	-	350.8721	-	70	0.1995
101H3-225	Single	1	1	1	1	NRHO	LLO	338.2612	338.2612	70	0.20694
124H3-225	Single	1	1	1	1	NRHO	LLO	169.1306	169.1306	35	0.20694
102H3-225	Single	1	1	1	1	ELFO	NRHO	310.1499	310.1499	70	0.22526
125H3-225	Single	1	1	1	1	ELFO	NRHO	155.0748	155.0748	35	0.22526
78H3-225	Single	1	1	1	1	ELFO	-	603.7834	-	140	0.23187
84H3-225	Single	1	1	1	1	ELFO	-	301.8917	-	70	0.23187
85H3-225	Single	1	1	1	1	NRHO	ELFO	308.2375	308.2375	70	0.23315
117H3-225	Single	1	1	1	1	NRHO	ELFO	150.1185	150.1185	35	0.23315
79H3-225	Single	1	1	1	1	LLO	-	598.5023	-	140	0.2335
87H3-225	Single	1	1	1	1	LLO	-	299.7511	-	70	0.2335
29H3-225	Single	1	1	1	1	ELFO	LLO	347.2142	347.2142	85	0.24481
58H3-225	Single	1	1	1	1	ELFO	LLO	173.6071	173.6071	42.5	0.24481
103H3-225	Single	1	1	1	1	NRHO	LLO	282.4696	282.4696	70	0.24781
118H3-225	Single	1	1	1	1	NRHO	LLO	141.2348	141.2348	35	0.24781
104H3-225	Single	1	1	1	1	ELFO	LLO	267.9146	267.9146	70	0.26128
126H3-225	Single	1	1	1	1	ELFO	LLO	133.9572	133.9572	35	0.26128
105H3-225	Single	1	1	1	1	ELFO	NRHO	256.8738	256.8738	70	0.27251
119H3-225	Single	1	1	1	1	ELFO	NRHO	128.4369	128.4369	35	0.27251
140H3-225	Single	1	1	1	1	EMO	-	613.07786	-	170	0.27731
25H3-225	Single	1	1	1	1	EMO	-	306.51893	-	85	0.27731
106H3-225	Single	1	1	1	1	LLO	NRHO	245.7889	245.7889	70	0.2840
127H3-225	Single	1	1	1	1	LLO	NRHO	122.8944	122.8944	35	0.2840
38H3-225	Single	1	1	1	1	LLO	NRHO	296.0448	296.0448	85	0.28668
57H3-225	Single	1	1	1	1	LLO	NRHO	148.2474	148.2474	42.5	0.28668
110H3-225	Single	1	1	1	1	ELFO	NRHO	221.4859	221.4859	70	0.31609
128H3-225	Single	1	1	1	1	ELFO	NRHO	110.743	110.743	35	0.31609
107H3-225	Single	1	1	1	1	ELFO	LLO	214.9679	214.9679	70	0.32621
129H3-225	Single	1	1	1	1	ELFO	LLO	107.2939	107.2939	35	0.32621
49H3-225	Single	1	1	1	1	LLO	ELFO	245.9445	245.9445	85	0.34561
50H3-225	Single	1	1	1	1	LLO	ELFO	122.9722	122.9722	42.5	0.34561
108H3-225	Single	1	1	1	1	NRHO	-	184.1160	-	70	0.36025
123H3-225	Single	1	1	1	1	LLO	NRHO	97.20826	97.20826	35	0.36025
104H3-225	Single	1	1	1	1	ELFO	NRHO	170.3782	170.3782	70	0.41085
120H3-225	Single	1	1	1	1	ELFO	NRHO	85.1891	85.1891	35	0.41085
78H3-225	Single	1	1	1	1	EMO	-	181.5347	-	140	0.86665
88H3-225	Single	1	1	1	1	EMO	-	90.76733	-	70	0.86665
109H3-225	Single	1	1	1	1	EMO	-	169.7885	-	170	1.0010
122H3-225	Single	1	1	1	1	EMO	-	84.894415	-	85	1.0010
79H3-225	Single	1	1	1	1	EMO	-	73.0895	-	140	1.7525
92H3-225	Single	1	1	1	1	EMO	-	36.04847	-	70	1.7525

Fig. 8. OTV service catalog.

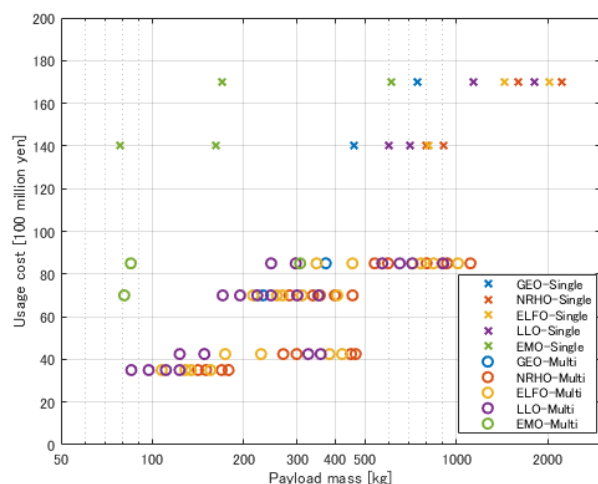


Fig. 9. Summary of OTV service catalogue.

5.3. Comparison multiple mission

This subsection shows the comparison of economic efficiency with OTV and without OTV. One strong advantage of using OTV is that the total cost of multiple missions can be reduced and the commonly designed OTV can make space transportation more efficient. The following various missions that the OTV applies are considered.

Mission example)

1. LNSS satellite 1, ELFO
2. Mars EDL&R spacecraft, EMO
3. SDA satellite, GEO
4. Lunar observation satellite, LLO
5. LNSS satellite 2, ELFO

Figure. 10 shows the mission mass, total cost, and cost per mission mass with and without OTV when above 5 missions are conducted. In order to evaluate as fairly as possible with OTV case and without OTV case, not cost per payload mass but cost per mission mass is evaluated. In this analysis, the cost includes both NRC and RC to consider the total cost. As shown in Fig. 10, mission mass with OTV is less than that without OTV because OTV has a redundant bus system compared to without OTV case. However, the total cost with OTV is approximately half of that of without OTV because with OTV case takes only one NRC, while without OTV case takes both NRC and RC for every launch. As a result, the cost per mission mass with OTV can be reduced by around 23 % compared to without OTV case after 5 missions are completed.

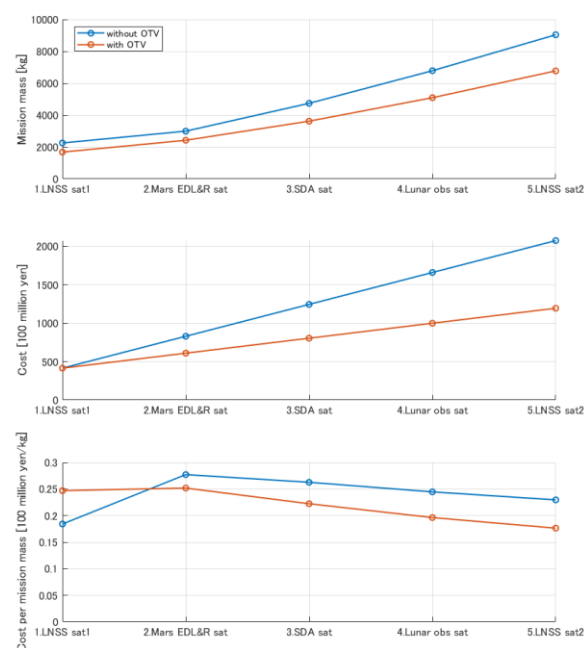


Fig. 10. Comparison of economic efficiency with and without OTV

5. Conclusion

In this paper, we proposed a method to evaluate economic efficiency when disposable OTVs that can be used for various target orbits are used for transportation in space. We formulated a multidisciplinary system design optimization problem that spans multiple domains, such as OTV subsystems and costs, as a multi-objective optimization problem, and constructed a framework to solve the multi-objective optimization problem using a genetic algorithm. By taking the average payload transportation mass to geostationary, lunar, and Mars orbits and the average of the respective transportation unit costs as the objective function, we were able to obtain a Pareto solution for OTV design that shows the trade-off between mass and unit cost. Among them, we showed that the transportation unit cost weighted by the expected transportation volume in 2030 is a good guideline for determining OTV design values. From this design solution, we obtained an OTV service catalog that shows the unit transportation cost and cost for various launch methods, rockets, and various target orbits such as from geostationary to the moon and Mars and quantitatively showed that the usage cost per user can be reduced by OTV piggybacking. Finally, we also showed that by using an OTV with a common design for multiple missions, non-recurring costs can be reduced, and the unit transportation cost of the mission mass can be reduced by about 23% across the five missions compared to without OTV case.

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