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MULTIDISCIPLINARY OPTIMIZATION OF SPACE TRANSPORATION SYSTEMS

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ABSTRACT

Cost estimation at the conceptual design phase is one of the most critical items to assess the feasibility of future space transportation systems and to establish the technical scenarios for them. Multidisciplinary optimization involving some subroutines as represented by cost estimation is strongly required to assess the reasonable and feasible systems. Therefore, “Systems Evaluation and Analysis Tool (SEAT)” is under development in JAXA. This study describes TRANSCOST 7.1 based cost estimation, compares with the life-cycle-costs of some space transportation systems’ concepts relatively, and discusses the effectiveness and limitations associated with this estimation. The partially reusable launch vehicle, TYPE-BR, is one of the most reasonable and feasible space transportation systems from the point of view of life-cycle-cost in this study.

1. Introduction

New and future space transportation systems to realize “Easy access to space” make us attractive. And they enable to expand human space activity from low earth orbit to moon and beyond. However, space launch vehicles are still in a developing process, compared to other ground and air transportation systems. And there are not so many space launch vehicles, not expendable (ELV) but reusable launch vehicles (RLV), all over the world. The flexible, suitable and various space transportation systems are required to achieve the stated activities [1]. From a practical standpoint, the much more expensive development, production and operation costs of them, richer experience and more sufficient period are required to achieve higher performance and reliability space transportation systems.

Performance, reliability, operability and life-cycle-cost associated with new space transportation systems are critical issues at the conceptual design phase [2]. Because, it is said that more than 70 to 85% of a transportation system’s life-cycle-cost depends on decisions made at this phase and/or preliminary design one [2-5]. Furthermore, if the incorrect concept will be selected at the conceptual phase, the latter design phase, like preliminary and/or detail design phase, will not correct a flawed concept design and selection [2, 5]. Conceptual design phase supported by a systems engineering process is very important. It is essential to investigate the mission requirements during this phase, and preparation of adequate databases and design tools is required for new space transportation system development.

Recent advances in computer technology and multidisciplinary optimization techniques enable us to realize more flexible design using software. A typical example is the Optimal Design Integration System (ODIN) developed by the NASA in 1970s [4], and it was carried out for SSTO system studies [6]. Also, the TRANSYS (TRANsportation SYStem) developed in Germany, investigated improvement of the performance of the Sanger concept [7]. Some companies have also recently been developing a concept study program [8, 9].

Japan Aerospace Exploration Agency (JAXA) has started developing a systems evaluation and analysis tool (SEAT) [10].for conceptual design studies. Unlike the above-mentioned programs, its main objective is to assist performing relative comparisons of various space transportation system concepts. SEAT evaluates various system concepts against the same design goals using same analytical methods and evaluation criteria, allowing the most promising candidates to be selected. Other objectives are to identify required technologies, and to establish quantitative goals for improving present technologies to enable the systems to be realized.

Here, cost estimation as one of some subroutines incorporated into SEAT is focused on and described in this paper. The main purpose of this paper is to estimate primarily the life-cycle-costs of various space transportation systems designed conceptually by SEAT. And these life-cycle-costs are compared to assess the systems, not absolutely but relatively. Finally, this paper describes the development scenario from the point of view of cost, its present status and the critical issues, and future works.

2. Outline of SEAT

This SEAT is under development, including the following six subroutines: aerodynamics, propulsion, weight estimation, trajectory, thermal protection system (TPS) design and cost, as shown in Fig. 1[10]. And an optimizer controls the mentioned subroutines to iteratively optimize the design.

Especially, cost is one of the key objective functions at the conceptual design phase. Because, it is said that more than 70 to 85% of a transportation system's life-cycle-cost depends on decisions made at this phase and/or preliminary design one [2-5]. Furthermore, cost possibly affects the concrete mid/long-term technological scenarios for JAXA that encountered the budget cuts. The reasonable and feasible life-cycle-costs are required for realizing the future space transportation systems.

Cost estimation model is fundamentally based on TRANSCOST 7.1[11], as described in the following chapter 4 in detail, and is developed and incorporated into SEAT. The cost indicates the summation of the development, production and operation costs as life-cycle-cost in this study.

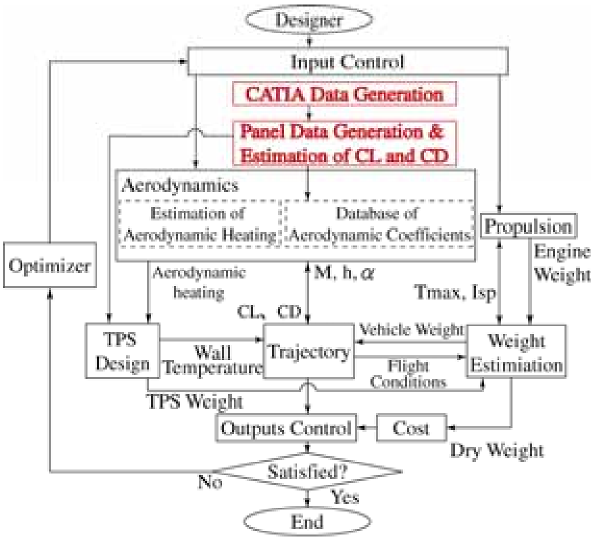

Fig. 1: Conceptual Figure of SEAT (Systems Evaluation and Analysis Tool)

3. Space Transportation Systems

Several RLVs are refined and studied with this SEAT. Our final goal of this study is to select the optimized vehicles to achieve the mission to 1 Mg payload into Low Earth Orbit (LEO) as sample. The following four types shown in Fig. 2 to Fig. 5 are focused and discussed to compare the life-cycle-costs relatively and extract the limitations and problems about the TRANSCOST based cost estimation [11].

"TYPE-XX" is defined as the vehicle type in this study. The first and second characters of "-XX" indicate the first and second stage vehicle types, respectively. The first vehicle is called as "TYPE-R" for "Single-Stage-to-Orbit (SSTO)", and the second one is "TYPE-RR" for "Two-Stage-to-Orbit (TSTO)" as shown in Fig. 2 and Fig. 3, respectively. They are vertically take-off and horizontally landing (VTHL). These types are mainly propelled by liquid propellant rocket engines, and "-R" indicates the "rocket propulsion" and the single stage vehicle. Here, existing LE-7 engine as liquid rocket engine is mounted on the TYPE-R and TYPE-RR. Green colored vehicle is the first stage of TYPE-RR to fly back after the separation in Fig. 3.

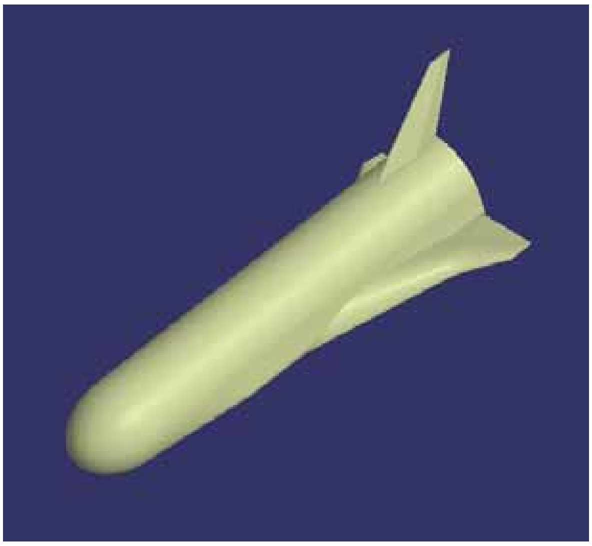

Fig. 2: TYPE-R (SSTO/VTHL) Configuration

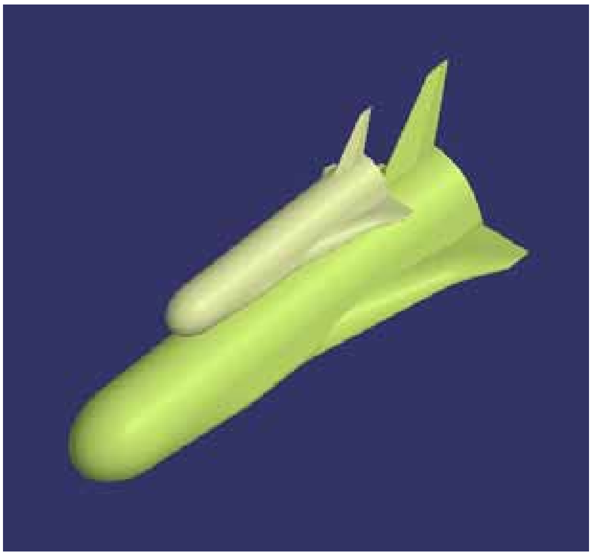

Fig. 3: TYPE-RR (TSTO/VTHL) Configuration

The third one is "TYPE-BR" for partially expendable and reusable launch vehicle, "Three-Stage-to-Orbit (P-ThSTO)" that is mainly propelled by liquid propellant rocket engines, LE-7, and/or assisted by some solid rocket boosters (SRBs). In this study, TYPE-BR has no SRBs as shown in Fig. 4. TYPE-BR takes off vertically and lands horizontally (VTHL). The orange colored first and second stages with LE-7 engines in Fig. 4 are similar to the ELV like H-IIA; on the other hand third stage is the orbiter that carries the payload to the designated orbit and returns to earth by gliding without engine thrust as well as HOPE-X (H-II Orbital Plane Experiment) [12].

The fourth one is the same "TYPE-TR" type as TSTO "TYPE-RR", but the green colored first fly-back booster stage is only propelled by "Pre-Cooled Turbo Jet engine (PCTJ)" that breathes the air from the atmosphere as shown in Fig. 5. TYPE-TR takes off and lands horizontally (HTHL). This air-breathing engine "PCTJ" has no oxidant to deliver for itself, and the feature to decrease the total propellant mass. And these engine modules are mounted on the both sides of the fuselage, but they are not shown in Fig. 5.

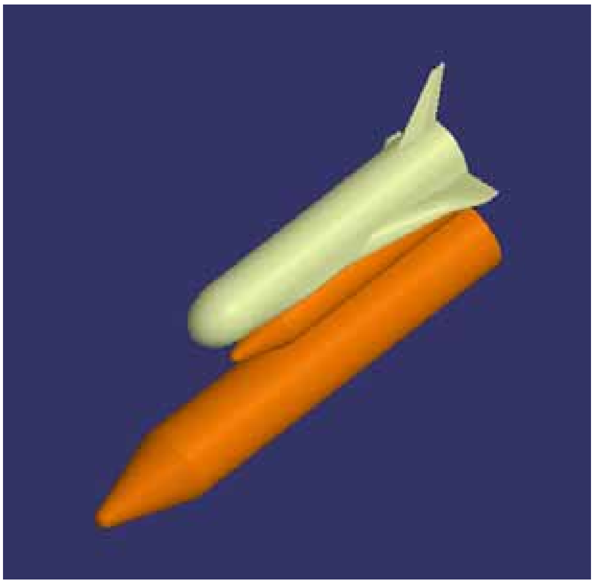

Fig. 4: Partially reusable launch vehicle, TYPE-BR without SRBs configuration (P-ThSTO/VTHL)

Fig. 5: TYPE-TR (TSTO/HTHL) Configuration

4. TRANSCOST based Cost Estimation

This chapter describes the outlines and characteristics of the TRANSCOST 7.1 based cost estimation [11]. TRANSCOST 7.1 is a statistical, analytical and top-down model for cost estimation and economical optimization of launch vehicles. This model is based on the past various vehicles involving the airplanes, fighters and launch vehicles and various propulsion systems all over the world, from 1963 to 2002. The following sections in this chapter describe the basic principle, how to use this cost estimation model and which technical factors can be effective and ignored to compare with relatively.

4.1. Cost Estimation Relationship

The statistical and analytical models are introduced to estimate the cost of vehicles and/or propulsions. Basic formula is written as the cost estimation relationship (CER):

$$C = a \cdot M^x \cdot \prod f_i \qquad (1)$$

With C = cost in Man-Year (MYr), a = system-specific constant value, M = mass in kg, x = system-specific cost-to-mass sensitivity factor and f_i = technical assessment and/or correction factors that depends on the technical quality, vehicle and/or propulsion type and learning factor for mass production and so on, as shown in Table 1. These coefficients, a and x, are statistically derived from the actual costs as mentioned.

Technical factors	section	remarks
f_0	4.1.2.	System engineering/integration
f_1	4.2.	Development Standard
f_2	4.2.	Technical Quality
f_3	4.2.	Team Experience
f_4	4.3.	Cost Reduction
f_6	4.1.2.	Cost Growth about Schedule
f_7	4.1.2.	Cost Growth about Contractors
f_8	4.1.2.	Productivity for Each Country

Table 1: Technical factors' list

4.1.1. Man-Year Value

MYr effort is used as cost value in this study. This MYr value is defined as the relevant total project costs divided by number of fully accounting people or the total annual net turnover (excluding subcontracts) divided by number of technical personnel (excluding administration and management) for specific company. MYr is introduced, because firm cost data which is valid internationally, independent from the time, periods and the different currencies and independent from the annual changes due to inflations and the other factors such as currency conversion rate fluctuations.

However, finally in this study, the absolute MYr value can be ignored, because the relatively comparisons are performed to assess the feasible and reasonable vehicles based on the same criteria.

4.1.2. System Engineering Factors

System engineering factors, f_0, and f_6 to f_8 are introduced to improve accuracy of estimation. The system engineering factor f_0 depends on the vehicle stage number. The factor f_6 depends on development schedule delay, f_7 on the contract number and f_8 on the country productivity. Each criterion is in detail listed on the handbook of TRANSCOST 7.1[11]. Finally the stated factors excluding f_0 can be ignored in case of the relative comparison, because f_6 and f_7 are estimated as an assumption, and f_8 is same value, because it depends on the country status.

4.2. Development Cost

Development cost estimation relationship is fundamentally based on the equation (2) as follow:

$$C_{DEV} = a \cdot M^x \cdot \prod_{i=1}^{3} f_i \qquad (2)$$

Especially, three technical factors are introduced to estimate the development cost as follow: development standard factor, f_1, technical quality factor, f_2, and team experience factor, f_3.

At first, technical quality factor f_2 depends on the kinds of the vehicle and propulsion system, for example, the net mass fraction of the vehicle, the number of firing test for qualification and acceptance, and furthermore the designated reliability.

Secondly, there is a certain level of correlation between the development standard factor f_1 and team experience factor f_3. Each criterion for f_1 and f_3 is listed on the handbook of TRANSCOST 7.1[11]. If a team had gone through a successful project, f_1 and f_3 would be concurrently lower than 1.0 with this type of project. Here, f_1 x f_3 indicates that the team with superior or related experience can reduce the development cost with same type of project.

However, the almost same development project is not usually executed successively, because the successful development project will be shifted to the production phase or the project with no success will be cancelled in general [13]. If a team with superior experience, $0.7<f_3<0.8$, will face to the minor or major modification, $0.4<f_1<0.6$, the state of the art, $0.9<f_1<1.0$, and the quite new technical challenging project, $1.3<f_1<1.4$, finally f_1 x f_3 changes from 0.3 to 1.2 gradually as shown in Fig. 6.

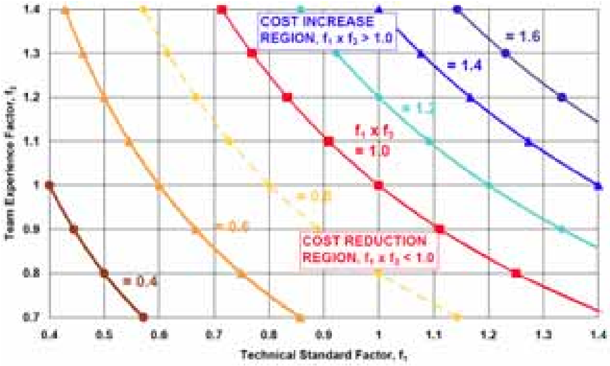

Fig. 6: Correlation between f_1 and f_3 factors

On the other hand, sometimes after a project completion any members of a team will switch positions with the experts or rookies keeping or enhancing the team experience for next project. The usual long-term project for aerospace development makes the stated personnel reshuffle. The f_3 depends on the team members' quality. If a partially different team or a team without superior experience will face to next one, f_3 is usually slightly higher than 1.0, and if some sophisticated members are involved in a team, f_3 keeps the same level or is the slightly lower than 1.0.

Consequently, from the stated point of view, it is not possible in Japan that significant cost reduction by f_1 x f_3 will be achieved, because not sophisticated experiences but the successive team conditions are substantially required. Finally, total development cost for each vehicle type is shown in equation (3):

$$C_{DEV(TYPE-XX)} = C_{DEV-V} + C_{DEV-E} + C_{DEV-B} \tag{3}$$

With C_{DEV-V}, C_{DEV-E} and C_{DEV-B} are the vehicle, engine and booster development costs, respectively. In this study, the effect of the stated technical factors excluding the technical quality factor f_2 can be ignored. Because there are not sufficient sophisticated experiences on the stated vehicle types' development in Japan, excluding 1st and 2nd stage for TYPE-BR like H-IIA. Furthermore, relative comparison is performed in the following sections.

4.3. Production Cost

Production cost estimation relationship is also same as the development cost, but another technical factor is introduced to estimate the production cost as shown in equation (4):

$$C_{PRO} = a \cdot M^x \cdot f_4 \cdot n \tag{4}$$

With n = production number and f_4 = cost reduction factor. Here, cost reduction factor f_4 as a function of the learning factor p and production number n is shown as follow. Learning factor p is fundamentally defined, based on simple economical principle. The more production number n increases, the less cost reduction factor number f_4 decreases. That is, it indicates the cost reduction.

However, only one RLV vehicle is produced, and then the effect of the cost reduction factor f_4 can be ignored in this study, n=1 and f_4=1. On the other hand, the production number of propulsion mounted on these vehicles is so many, and it is easy to see the effect of the cost reduction factor. Finally, total production cost for each vehicle type is shown in equation (5):

$$C_{PRO(TYPE-XX)} = C_{PRO-V} + C_{PRO-E} + C_{PRO-B} \tag{5}$$

With C_{PRO-V}, C_{PRO-E} and C_{PRO-B} are the vehicle, engine and booster production costs, respectively.

4.5. Direct Operation Cost

Some operation costs including direct, indirect operation costs, business charge and insurance costs are discussed and listed in the handbook of TRANSCOST 7.1[11]. In this study, the feasible and reasonable space transportation systems will be assessed based on the life-cycle-cost including not development and production costs but operation cost. Therefore, the direct operation costs (DOC) about the ground, propellant, mission and recovery operations are focused on. Some formulas about the stated DOC are listed in the handbook of TRANSCOST 7.1[11]. Finally, total operation cost for each vehicle type is shown in equation (6):

$$C_{OPR(TYPE-XX)} = C_{PLO} + C_{PROP} + C_{M} + C_{REC} \qquad (6)$$

With C_{PLO}, C_{PROP}, C_{M} and C_{REC} are the ground operation cost, propellant cost, launch, flight and mission operation cost and recovery operation cost, respectively. Especially, the launch per annum, LpA, is incorporated into each formula for direct operation cost. It is the cost driver for the cost per flight to assess the life-cycle-cost. In this study LpA is 5, because it is assumed that the preliminary and possible target for RLV surpasses the existing ELV, H-IIA.

4.6. Life-Cycle-Cost

As stated, the development, production and operation costs of the vehicle and propulsion are calculated by the stated formulas. Finally, the equation (7) is introduced to assess the life-cycle-cost for each launch vehicle.

$$C_{LCC(TYPE-XX)} = C_{DEV} + C_{PRO} + C_{OPR} \qquad (7)$$

With C_{LCC} is defined as the life-cycle-cost in this study.

5. Relative Life-Cycle-Cost Estimation

5.1. Design Example

The relevant vehicle is launched from the Equator, and reaches a circular 0-degree inclination 200 km altitude orbit. The trajectories are then constrained within the vertical plane. The atmosphere exists below 90 km altitude, and the vehicle will be thrown into the perigee of the Hohmann transfer orbit at the exit of the atmosphere. The fuel used on the Hohmann transfer is not taken into account. As flight conditions at the perigee, inertial velocity and inertial flight path angle are set as 7937.5 m/s and 0 degrees respectively. The performance index is launch weight for all cases.

The mentioned design example demonstrates the comparison of space transportation system concepts by optimally designing the single-stage-to-orbit (SSTO), two-stages-to-orbit (TSTO), and partially reusable and three-stages-to-orbit (P-ThSTO).

5.2. Space Transportation Systems' Specs

Fig. 7 indicates the relative vehicle size comparison and the relative specifications are listed on the Table 2. The number indicates the ratio of each vehicle specification to the TYPE-BR orbiter specification. These vehicle types are optimized by SEAT at the given design example as stated in chapter 3. The cost estimation based on the each vehicle and propulsion weight is performed as offline in this study, as shown in Fig. 1.

TYPE-XX	-BR	-R	-RR	-TR
Total Mass	1.000	10.71	1.091	1.499
1st stage length	1.506	4.850	2.025	5.194
2nd stage length	0.906	N/A	1.100	1.788
Orbiter length	1.000	N/A	N/A	N/A

Table 2: Relative Vehicle Size and Mass Comparison

5.3. Relative Estimation for Life-Cycle-Cost

TYPE-BR is treated as a baseline vehicle in this study, because the first and second stage external tanks of TYPE-BR are similar to the existing ELV like H-IIA, as shown in Fig. 4 and Fig. 7. Here, development, production and operation costs, finally, the total cost as life-cycle-cost are compared relatively.

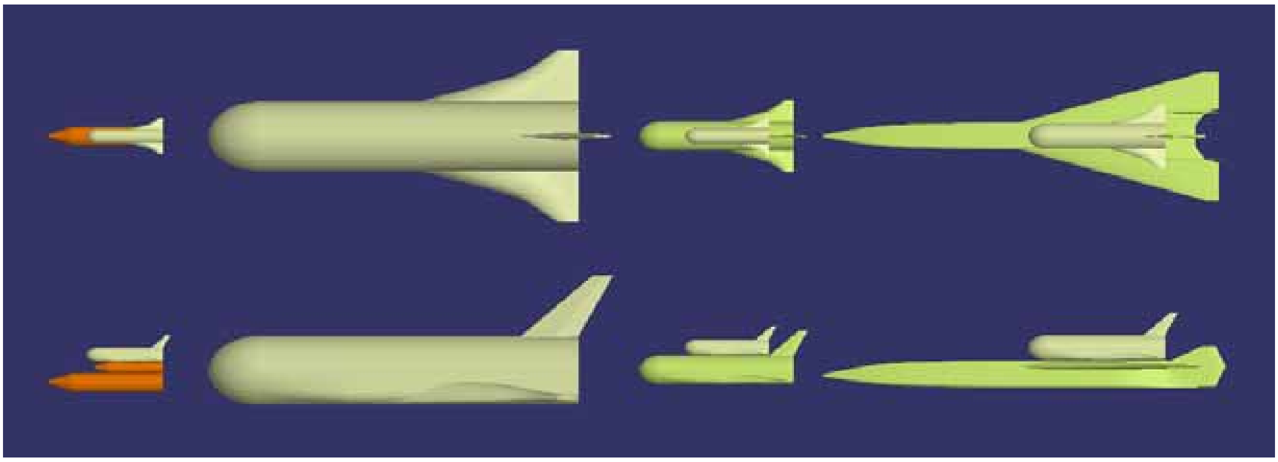

Fig. 7: Relative Vehicle Size Comparison (starting from the left, TYPE-BR, -R, -RR and -TR)

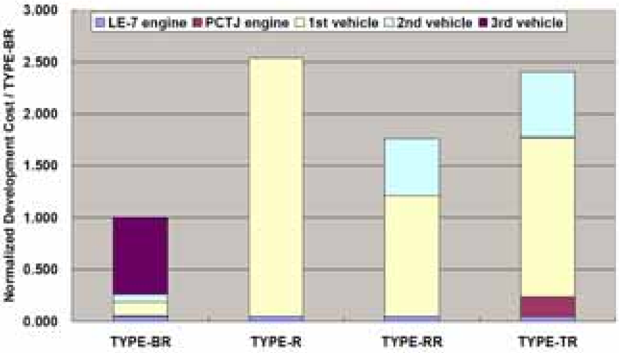

Fig. 8: Relative Development Cost Comparison

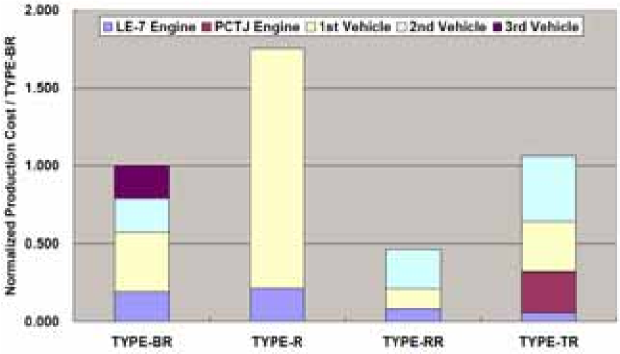

Fig. 9: Relative Production Cost Comparison

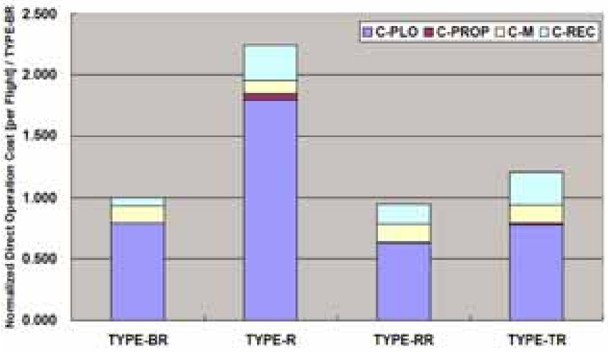

Fig. 10 Relative Direct Operation Cost (DOC) Comparison

At first, Fig. 8 shows the development costs for each vehicle stage and propulsion. Propulsion development cost excluding PTCJ is not so high, because derivative LE-7 engine is used. Each vehicle development cost is so expensive, because of so large, heavy vehicle for fly-back and re-entry.

Secondly, Fig. 9 shows the production cost. As development cost in Fig. 8, TYPE-R production cost is significantly expensive, whereas TYPE-RR production cost is less expensive than TYPE-BR. Because the first and second stage external tanks of TYPE-BR are expendable, therefore the engines and vehicles installed on the reusable orbiter have to be produced at each flight. Even if the cost reduction factor f_4 by mass production has effect on the unit production cost reduction, total production cost for expendable parts accounts for about 80% for TYPE-BR production cost to achieve the mission at 5 LpA, as shown in Fig. 9.

On the other hand, TYPE-RR production cost is about half of TYPE-BR. TYPE-RR has the advantage from the point of view of reusability, because of a higher LpA, more the first and second stage external tanks of TYPE-BR have to expend at each flight. It indicates the total production cost increase.

TYPE-TR is almost same as TYPE-BR for production costs in case of 5 LpA mission. If TYPE-TR has proven the possibility for reusability more than 5 LpA, TYPE-TR has an advantage over TYPE-BR from the point of view of total production cost.

Thirdly, Fig. 10 shows the DOC. There is not so discrepancy between these types excluding TYPE-R. As shown in Table 1, TYPE-R has the heaviest vehicle dry mass and this whole vehicle has to be re-entry and fly-back to the Earth; therefore ground and recovery operation cost, C_{PLO} and C_{REC}, is so expensive. In case of the other types, the second or third stage vehicle only re-entry, therefore recovery operation cost is not so expensive. Consequently, the lift-off weight and re-entry vehicle mass have to be minimized to minimize the direct operation costs by considering the LpA.

Finally, Fig. 11 shows the total cost as life-cycle-cost. The partially reusable launch vehicle, TYPE-BR, is one of the most feasible and reasonable concept from the point of view of life-cycle-cost at the given design example. Each development cost accounts for over 90% of total cost. Although, at lower LpA, the production and operation costs are negligible against the development cost, they are not negligible at higher LpA in the far future and have effects on cost estimation for the commercial launch. Development cost reduction is one of the critical issues to realize the next generation space transportation system with high reliability and technical quality.

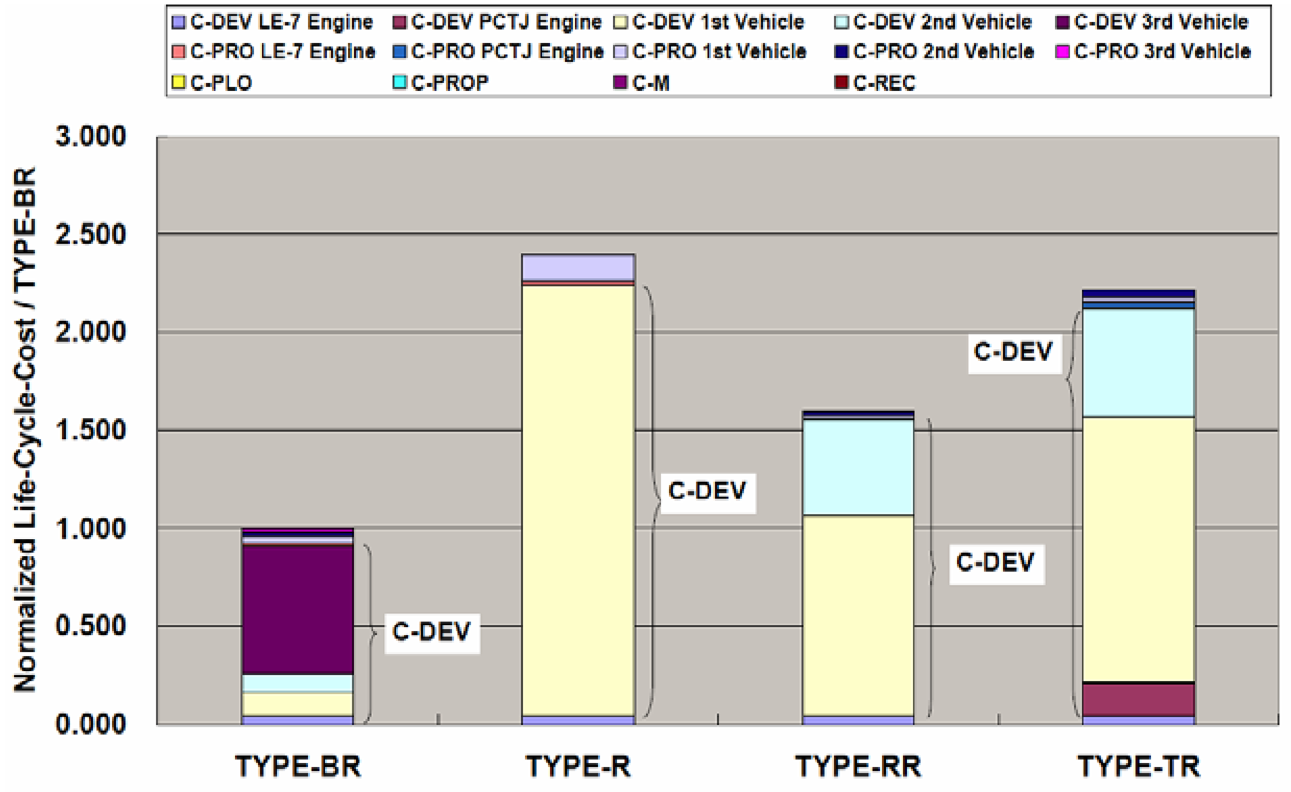

Fig. 11: Relative Life-Cycle-Cost Estimation

6. Conclusions and Future Works

The following results and conclusions are attained in this study.

1. TRANSCOST based cost estimation is performed to compare with some space transportation system concepts relatively.

2. The partially reusable launch vehicle, TYPE-BR, is one of the most feasible and reasonable concept from the point of view of life-cycle-cost in this study.

3. Development scenarios for the future space transportation systems can be appropriately proposed by this life-cycle-cost estimation incorporated into SEAT. Especially, it can be clarified which fundamental technologies are considerably required to realize new space transportation system.

It is significantly necessary for us to do cost estimation study for future space transportation systems successively and/or as occasion may demand.

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