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Low-cost management aspects for developing, producing and operating future space transportation systems

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Abstract

It is believed that a potential means for further significant reduction of the recurrent launch cost, which results also in a stimulation of launch rates of small satellites, is to make the launcher reusable, to increase its reliability and to make it suitable for new markets such as mass space tourism. Therefore, not only launching small satellites with expendable rockets on non-regular flights but also with reusable rockets on regular flights should be considered for the long term. However, developing, producing and operating reusable rockets require a fundamental change in the current "business as usual" philosophy. Under current conditions, it might not be possible to develop, to produce or to operate a reusable vehicle fleet economically. The favorite philosophy is based on "smart business" processes adapted by the authors using cost engineering techniques. In the following paper, major strategies for reducing costs are discussed, which are applied for a representative program proposal.

1. Introduction

Space transportation is one of the most essential elements for enabling activities in space. For current rockets, reliability is too low and launch cost is too high, when compared to aircraft operations. Reusable launch vehicles (RLVs) could solve these deficiencies and are investigated by many companies. RLVs are designed for quick-turnaround operations that will allow for a higher volume and launch rate, resulting in economies of scale. Assets of RLVs are low operating costs for high launch rates, high reliability and satisfactory ecological compatibility. Known disadvantages of RLVs are high development costs and high operating costs for low launch rates similar to Space Shuttle system operations [1,2].

RLV concepts proposed for development present a variety of launch, landing and propulsion concepts. Several vehicles employ a spaceplane design that might take off and land horizontally like an airplane. These designs generally use upper stages to carry

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Nomenclature

B$	billion US dollars (dimensionless)
CER	cost estimation relationship (dimensionless)
CpF	cost per flight (M$/flight)
DOC_{fix}	fix direct operating cost (M$/flight)
DOC_{var}	variable direct operating cost (M$/flight)
ELV	expendable launch vehicle (dimensionless)
GTO	geosynchronous transfer orbit (dimensionless)
HL	horizontal landing (dimensionless)
IOC	indirect operating cost (M$/flight)
Mg	mega grams (dimensionless)
MY	man year (dimensionless)
M$	million US dollars (dimensionless)
RLV	reusable launch vehicle (dimensionless)
ROI	return on investment (dimensionless)
TSTO	two stage to orbit (dimensionless)
VL	vertical landing (dimensionless)
VTO	vertical take-off (dimensionless)

payloads to orbit, while the spaceplane remains on a suborbital trajectory. Many of these vehicle concepts are conceived with expectation that there will be significant demand for launches of communication satellites, some hope to serve other new markets such as space station supply and flights for space tourists [2].

Representative RLV concepts are Hopper Plus for suborbital missions and Kankoh Maru Plus for orbital missions as shown in Fig. 1. Hopper Plus is assumed to perform a suborbital trajectory with 30 passengers or carry an expendable upper stage with a 7.5 Mg payload to GTO launched from Kourou spaceport. Initial operational year is assumed to be 2013. Kankoh Maru Plus might perform an orbital 24 h trajectory with 50 passengers or transport a 2.5 Mg payload to GTO. Initial operational year is assumed to be 2030.

2. Cost engineering tools

Tools used for cost estimation are TRASIM 2.0 [3] and TRANSCOST 7.0 [4], which are statistical–analytical models for cost estimation and economical optimization of launch vehicles. Using both tools each other for reciprocal verification of results leads to a cost estimation process of high quality. Tool used for financial estimation is FINANCE 1.0 [5,6] to process the results achieved from cost estimation models.

2.1. Cost estimation relationships

The cost models are based on cost estimation relationships (CERs) with the basic form shown in Eq. (1) CERs are equations, which are often mass-related and contain different parameters. These parameters have to be determined by the user. CERs are derived from actual costs including cost of unforeseen technical problems and delays.

Employed cost models use man-year (MY) effort as cost value. This is transformed by using a cost conversion value d to equivalent US dollars for fiscal year 2000 concerning field of occupation: for development 1 MY is equivalent to \$205 000, for production 1 MY is equivalent to \$200 000, for operation 1 MY is equivalent to \$220 000 and for unknown data 1 MY is equivalent to \$208 000 representing the average of above values.

$$C = aM^x \prod f_i d \tag{1}$$

with

C	cost (M$)
a	system-specific constant value (MY/Mg^x)
M	reference mass (Mg)
x	system-specific cost/mass factor (-)
f_i	assessment factors (dimensionless)
d	cost conversion value (M$/MY)

For verification of the models, the space shuttle, which is the only existing (but only partially) reusable launch vehicle in operation, has been simulated in parallel.

2.2. TRASIM model

The TRASIM 2.0 model is a bottom–up cost analysis, which means that costs are determined on a

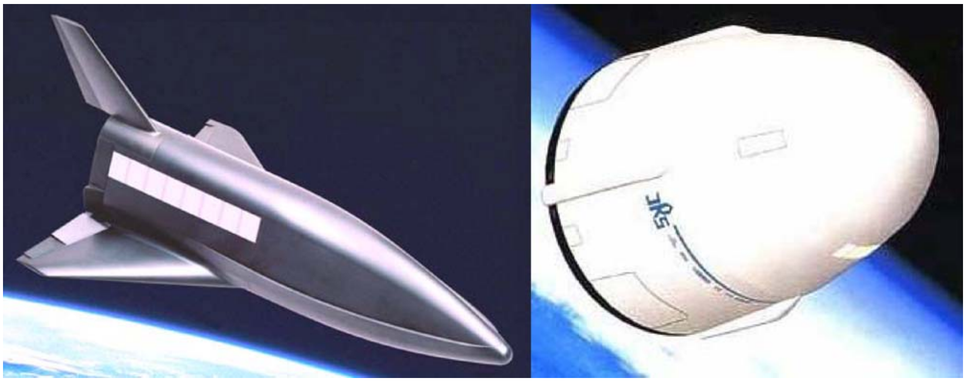


Fig. 1. Representative RLV concepts for suborbital (left) and orbital (right) missions.

subsystem level. Its strength is the possibility for the user to identify the cost influence of each subsystem on the space transportation system.

This model is a tool for the analyses of the entire life-cycle of a fleet of space transportation systems on an annual basis. It can consider transportation activities between nine transportation nodes of five different space transportation systems consisting of up to three stages with five payload categories each employed in eight different mission modes.

The model is available as a program as shown in Fig. 2 processing about 380 input values to determine costs. Applying this model from 1989 has led to refinements that have been incorporated into the current version TRASIM 2.0.

2.3. *TRANSCOST model*

The TRANSCOST 7.0 model is a top–down cost analysis, which means that costs are determined on a system level. Its strength is to provide the user with a first-order of magnitude of system costs with an accuracy of ±20% [2].

The model is available as a handbook containing 180 graphs as shown in Fig. 3 and 30 tables to determine life-cycle costs on an average basis. It has been established for the initial conceptual design phase. The model is based on a 40-year database from US, European and Japanese space vehicle projects.

2.4. *FINANCE model*

The FINANCE 1.0 model is a finance analysis to determine business performances of investigated vehicles. Its strengths is the capability to transform financial data rows into clear graphs and allows to check the sensitivity of each parameter to the overall performance.

The model is available as a program as shown in Fig. 4. It allows determining and optimizing key economic data such as return on investment (ROI), break-even point, receipts, yields, taxes and credits. Ticket prices are determined by an integrated ticket price passenger demand model but prices can also be entered manually.

3. Cost engineering method

For assessment of a vehicle's success, it is important to estimate realistic launch cost. This is done by calculation of life-cycle costs for a simulated scenario. Life-cycle costs include development cost, vehicle production cost, operating cost and abolition cost. Depending on the contracts, development and abolition costs are covered by contract of a governmental agency [1].

- Development costs are non-recurring. They include at least one prototype, testing as well as fabrication rigs and tools cost, since, normally, a prototype unit is included in a development program requiring tools and rigs for prototype production.
- Production costs are recurring. They include the follow-on production.
- Operating costs are recurring. They include management, pre-launch operations, launch operations, mission control, propellants and ground transportation.

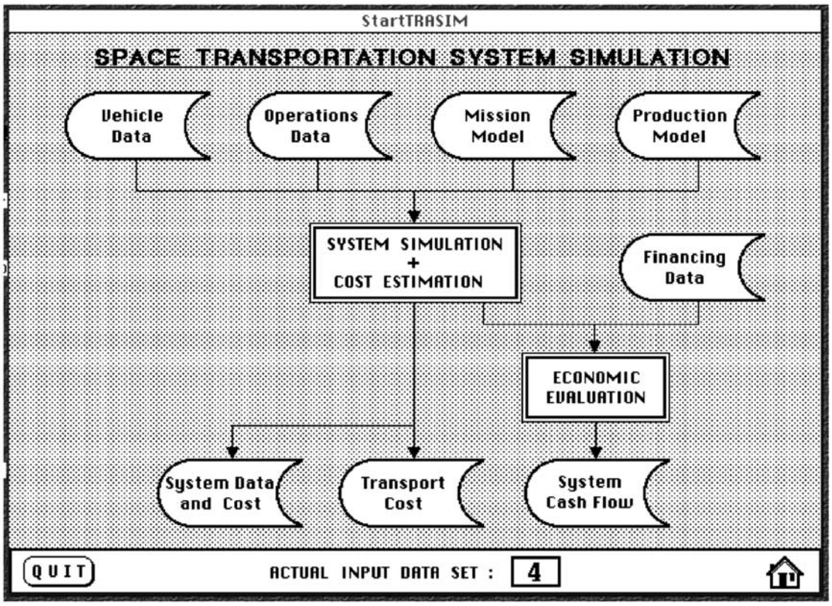


Fig. 2. TRASIM main input mask [3].

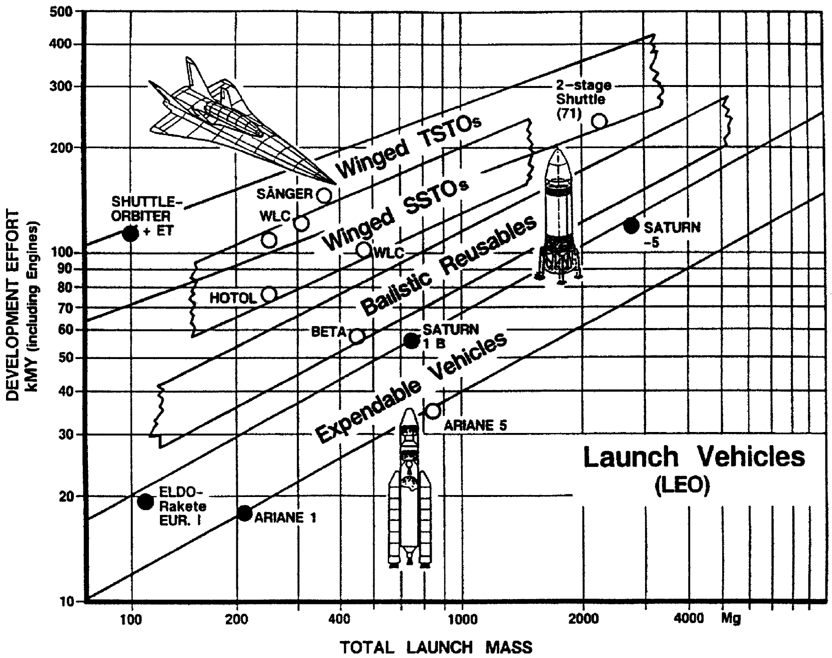
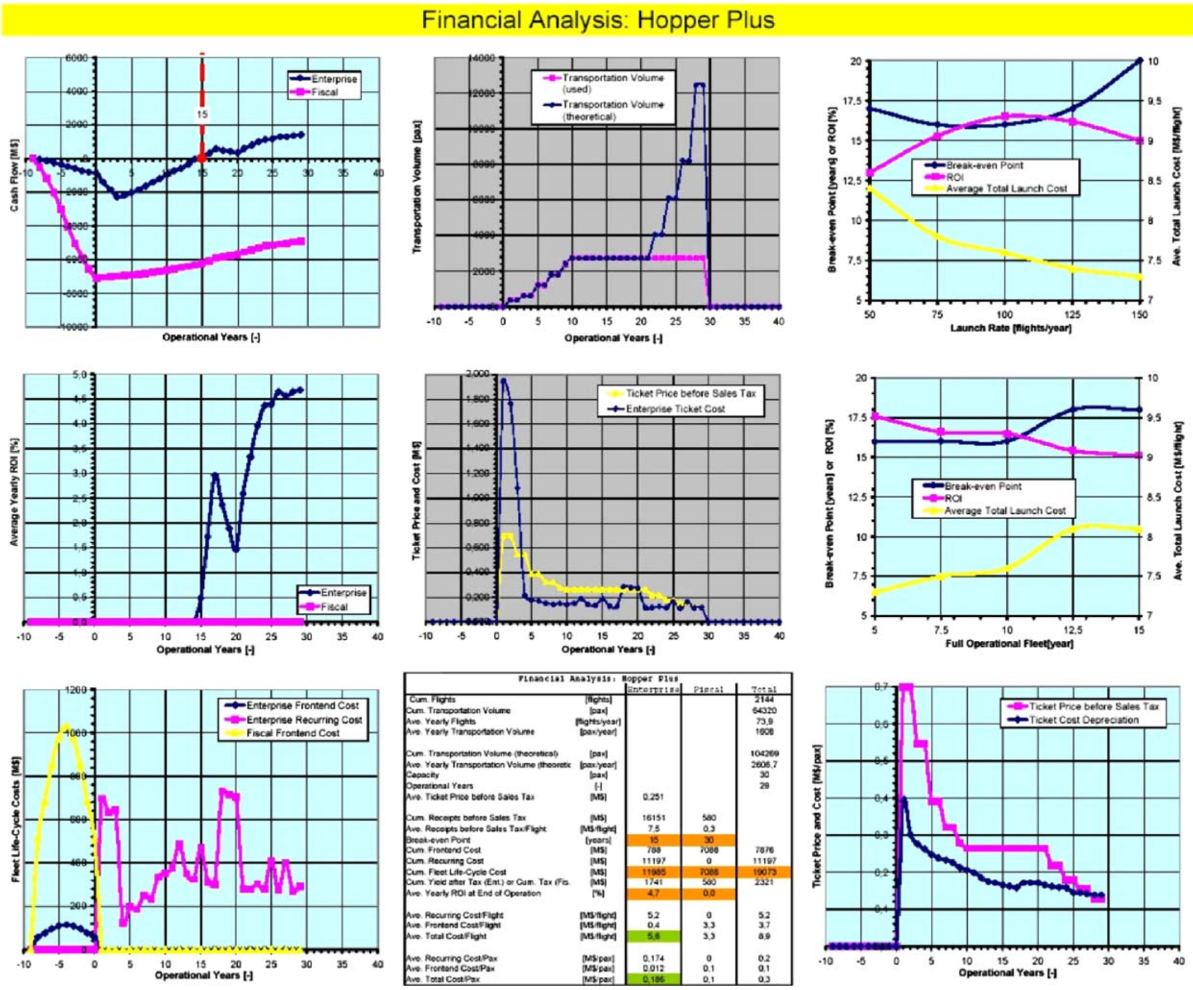


Fig. 3. Example of a TRANSCOST graph [4].



Financial Analysis: Hopper Plus		Enterprise	Fiscal	Total
Cum. Flights	[flights]			2144
Cum. Transportation Volume	[pax]			64320
Ave. Yearly Flights	[flights/year]			73,9
Ave. Yearly Transportation Volume	[pax/year]			1608
Cum. Transportation Volume (theoretical)	[pax]			104269
Ave. Yearly Transportation Volume (theoretic	[pax/year]			2606,7
Capacity	[pax]			30
Operational Years	[-]			29
Ave. Ticket Price before Sales Tax	[M$]	0,251		
Cum. Receipts before Sales Tax	[M$]	16151	580	
Ave. Receipts before Sales Tax/Flight	[M$/flight]	7,5	0,3	
Break-even Point	[years]	15	30	
Cum. Frontend Cost	[M$]	788	7088	7876
Cum. Recurring Cost	[M$]	11197	0	11197
Cum. Fleet Life-Cycle Cost	[M$]	11985	7088	19073
Cum. Yield after Tax (Ent.) or Cum. Tax (Fis.	[M$]	1741	580	2321
Ave. Yearly ROI at End of Operation	[%]	4,7	0,0	
Ave. Recurring Cost/Flight	[M$/flight]	5,2	0	5,2
Ave. Frontend Cost/Flight	[M$/flight]	0,4	3,3	3,7
Ave. Total Cost/Flight	[M$/flight]	5,6	3,3	8,9
Ave. Recurring Cost/Pax	[M$/pax]	0,174	0	0,2
Ave. Frontend Cost/Pax	[M$/pax]	0,012	0,1	0,1
Ave. Total Cost/Pax	[M$/pax]	0,186	0,1	0,3

Fig. 4. FINANCE output mask [5].

- Abolition costs are non-recurring. During the abolition phase, vehicles and ground facilities are scrapped, employees are dismissed and licenses are sold. In general, abolition costs are the balance between expenses and proceeds, which is compensated by variable direct operating cost (DOC_{var}) of one launch.

In business studies, it is common and useful to amortize development, production and abolition costs over fleet operation phase. Thus, development cost is represented by "development amortization cost", production cost is represented by "vehicle amortization cost" and abolition cost has a share in "technical support cost".

Operating cost is the sum of variable direct operating cost, fix direct operating cost and indirect operating cost as shown in Fig. 5.

- DOC_{var} are all those costs, which are dependent on the vehicle's utilization. For example, two launches instead of one means twice the propellant cost.
- Fix direct operating cost (DOC_{fix}) are all those costs, which are independent of the vehicle's utilization. In order to determine total direct operating cost per launch, DOC_{fix} is distributed over all

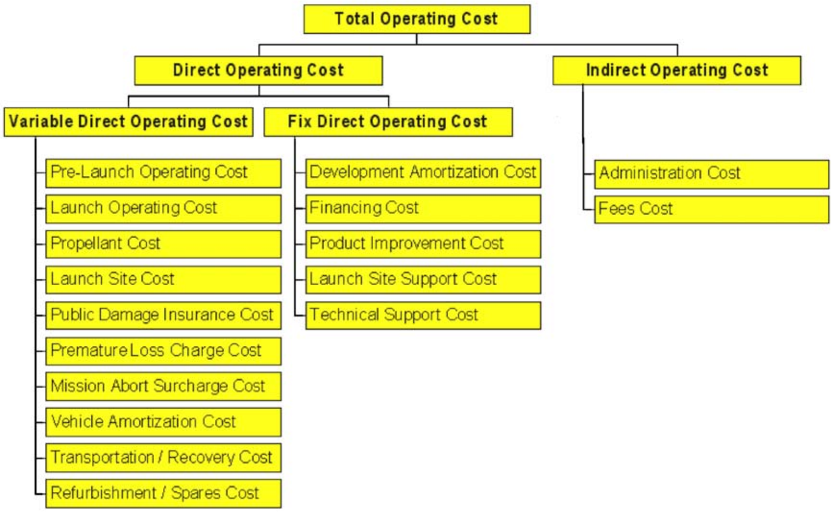


Fig. 5. Overview of operating costs.

launches of the fleet during life-cycle. For example, due to changing regulations during the fleet life-cycle, the vehicle has to be equipped with new safety equipment.

- Indirect operating cost (IOC) comprises all those costs that are not directly related to launch operations.

4. Cost-saving strategies

This study investigates costs of Hopper Plus and Kankoh Maru Plus for two different business cases namely “business as usual” and “smart business” processes.

A business case is a “tool” that supports planning and decision-making—including decisions about whether to buy, which vendor to choose and when to implement. Business cases are generally designed to answer the question: What will be the financial consequences by choosing X or doing Y? The organizational backbone of the case is a time line extending across years, as Fig. 6 suggests. This gives a framework for showing management how it can work to implement financial tactics: reduce costs, increase gains and accelerate gains [7].

For example, the marketing cost can be the same for different types of vehicles.

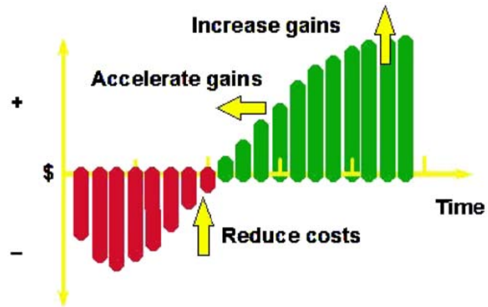


Fig. 6. Business case [7].

“Business as usual”costs in the aerospace sector are caused by over-specification, high bureaucracy, many design changes, extended schedules, parallel work on same topics, poor and mostly late communication and overmeetings beside necessary costs. Under these conditions, it was not possible to create a scenario to develop, to produce or to operate a reusable vehicle fleet for tourists economically.

The favorite philosophy is based on “smart business” processes adapted by the authors using cost engineering techniques developed by D.E. Koelle. The goal of cost engineering is to determine a vehicle design and its operation for minimum life-cycle costs.

Table 1
Selected strategies for reduced development cost

Name	Remark
Program organization	The organization principle for a development of a complex technical project requires a clear-cut prime contractor and subcontractor relationship with well-defined responsibilities. Several participating parallel contractors with coordination by the customer or an additional organization instead of a strong prime contractor lead to higher project cost. For example, reorganization of Space Shuttle operations responsibility to only one prime contractor reduced annual cost by 32% [4].
Type of contract	Award fee contracts are based on schedule milestones, technical performance, and final cost. They provide for an award when cost savings are achieved. This motivation for the contractor helps therefore to decrease development costs. On the other hand, a fixed price contract is more suitable for production-phase, because for development-phase it would cause critical delays in project schedules due to bureaucratic matters.
Annual funding profile	Funding distribution over the development period has a major cost impact. Optimum profile is a bell-shaped curve, which is used for this vehicle analyses. If the program is underfunded in the beginning, a longer schedule and therefore a cost increase will result.
Schedule deviation	History shows that a schedule extension by 20% will cause an average cost increase of 13%, while an accelerated schedule by 20% will cause an average cost increase of 8% due to the overtime and additional parallel work. For example, Space Shuttle orbiter development schedule was extended by 20% results in a cost growth of 22% [8].
Rapid phototyping	This strategy is favored by industry. Time- consuming and expensive detailed design and theoretical analyses efforts are replaced by early construction in order to verify the design as realized by Russian space projects. An example is the American SR-71 aircraft, which flew only 30 months after contract award.
Technology readiness	The idea is to use less advanced technology and existing components that will lead to lower development and production costs. Using subsystems with lower technology readiness status leads to higher project schedule uncertainties and risk of technical changes during development and therefore higher development costs. For the suborbital program proposal, the aim is to use existing Ariane 5 technology and infrastructure of Kourou Spaceport to the maximum extent possible.
Step-by-step method	This strategy is favored by government. A subscale test vehicle is built if the real-size program cannot be fully funded, or technology verification by a flight vehicle seems to be indispensable. An example is Delta Clipper DC-X experimental vehicle developed by McDonnell Douglas or Phoenix flight test demonstrator developed by EADS Space Transportation.
Mass estimates	A mass margin of 10% to the mass estimate of the initial design phase (Phase A) should be included. History shows, that the addition of a large number of secondary items as well as additional requirements coming up in the detailed design phase (Phase C), results in costs higher than estimated. For example, Space Shuttle orbiter experienced 25% [9] mass growth during development.
Vehicle concept	Using same assumptions, it shows that a ballistic rocket configuration (VTO/VL) needs the lowest development effort (reference = factor 1,0), while there is an increase in cost by a factor of 1.6 for a winged rocket configuration (VTO/HL), 2.1 for a parallel-staged winged TSTO rocket configuration and 3.1 for a horizontally launched TSTO concept [4], respectively.
Engine overdesigning	It has been verified that number of test firings performed during engine qualification program has the major impact on development cost and not the type of propellant or specific impulse. Effective operational engine reliability depends not only on number of qualification tests but also on operational thrust level used. The strategy is to overdesign engines by some 10% compared to the flight thrust level requirement. This increases mass and pre-development cost but allows reducing the number of qualification firings resulting in total development cost reduction. For example, jet engines are qualified through about 12 000 endurance cycles before flight-testing, thus achieving an operational reliability of 0.9999 [10]. Such a high number of tests would not be economical in case of rocket engines.

Table 2
Selected strategies for reduced production cost

Name	Remark
Annual production rate	When large units are built in a special facility as the only product, total annual cost is almost constant independent of number of units produced, caused by learning factor. An example is space shuttle system's external tank, where the difference between $340 million for six units per year and $380 million for 12 units per year [4] represents mostly the material cost. Cost savings could be achieved for RLVs by modular design of subsystems in particular tanks, hot structures and engines.
Timing	Different methods depending on launch rate should be strived for it to be economical. For a relatively low launch rate, all vehicles plus spares required should be produced in an optimum short time period (in batches) and put into storage until needed as applied for Hopper Plus. Production facilities are then converted and used for other projects. For a relatively high launch rate, a continuous production activity is maintained which means scheduled introduction of new vehicles into the program as assumed for Kankoh Maru Plus.
Engine Chamber	Very high engine chamber pressures of greater than 130 bar demand more advanced material and processing technologies and can increase production cost.
Propellant combination	Rocket engines featuring liquid hydrogen as fuel exhibit higher production costs than engines with other fuels.

Table 3
Selected strategies for reduced operating cost

Name	Remark
Pre-launch operations	Incorporation of a self-diagnosis system for vehicle and its engines enables a more aircraft-type maintenance operation.
Catastrophic failure	Catastrophic failure rate is caused by changes of materials, processes, component suppliers and new people over time. Loss rate value and related costs would be lower for a single-stage vehicle compared to a two-stage one owing to difficult stage separation maneuver. Failure rate of Space Shuttle flights is 1.0% (1 out of 100 flights). For Hopper Plus and Kankoh Maru Plus a failure rate of less than 0.1% (1 out of 1000 flights) must be demanded for first years of operation. It should be mentioned that loss of vehicle is not mandatory same as loss of vehicle including passengers.
Refurbishment	Refurbishment effort is growing with a higher number of life-time flights. Therefore, it should be researched in further studies the cost-optimized value of life-time flights. For Hopper Plus and Kankoh Mara Plus, cold structure number of reuses – and therefore number of lifetime flights — is assumed 600.
Launch site support	Ariane 4 and Ariane 5 operations at Kourou Spaceport requires a total staff of 1400 people for administration, management, security, facilities maintenance and general support. It should be achieved to operate Hopper Plus and Kankoh Maru Plus with a reduced staff and therefore costs by reorganization of participating organizations and companies: less parallel work, less bureaucracy and only one responsible management structure.
Flight rate	A higher flight rate leads to lower operation costs due to process improvement and learning curve effects. In case of Space Shuttle operations, a 30% flights per year (from 6 to 8 launches/year) leads to a 22% decrease in Cost per Flight (CpF). Hopper Plus would start with 12 launches per year in the beginning and would be increasing to 90 launches per year in the end of operation, while Kankoh Maru Plus would start with 25 launches per year increased to 2000 launches per year over time.
Payload capability	The higher the payload capability the greater is the cost saving potential for RLVs compared to Expendable Launch Vehicles (ELVs). Reason for this is that RLV costs are mainly determined by operations cost, which are less sensitive to vehicle size, while ELV costs are determined by production cost and therefore depends on vehicle size. However, due to market saturation a larger launch vehicle reduces launch rate, which increases specific costs. Additionally, development investment required will limit launch vehicle size.

Table 4
Comparison of cost estimates

Vehicle	Phase	Business as usual	Smart business	Savings (%)
Hopper Plus	Development	14.7 B$	7.9 B$	46
	Production (first unit)	1.2 B$	0.6 B$	50
	Operation (average)	30 M$/launch	5.6 M$/launch	81
Kankoh Maru Plus	Development	14.2 B$	9.7 B$	32
	Production (first unit)	0.8 B$	0.6 B$	25
	Operation (average)	24 M$/launch	2.7 M$/launch	89

This means that costs have to be taken into account as a main decision criterion for the whole program duration. Selected major strategies are discussed in Tables 1–3 , which have been applied to investigated reusable launch vehicles, Hopper Plus and Kankoh Maru Plus, for illustration.

5. Conclusion

If all 26 cost-saving strategies are applied, cost of governmentally contracted projects may be reduced drastically under favorable conditions, i.e. “smart businiess” processes, if compared with traditional “business as usual” costs as shown in Table 4.

One consideration to improve attractiveness of manned RLVs would be to use it for satellite payloads in initial phase of operation. Cash flow behavior might be very sensitive for initial phase because high production costs would cause huge debts, which have to be paid off by ongoing operations. High receipts from satellite payloads could avoid debts in the initial phase. Additionally, satellite launches are a good process to certify the vehicle and show its reliability before using it for humans. Therefore, RLVs should be compatible to serve other markets such as space station supply and satellites delivery phase flights for space tourists to achieve maximum benefit.

In historical context, a novel program such as Hopper Plus or Kankoh Maru Plus for a new market is important. Throughout history, thriving economies have relied on ready access to transportation to enable exploration and trade. In case of commercial aviation, this economic dynamo did not arise overnight. Over the last century, at least six generations of aircraft have been developed, starting with the Wright plane and ending with the new Airbus A380. Major technological advances led to aircraft that are more capable and new markets from mail, passenger service, package delivery and interstate commerce. Investment in space transportation could lead to similar results in the worldwide commercial space marketplace.

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