Some attempts at cost estimation of SpaceX's Starship

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Sang-Hyeon Choi[1], Jascha Wilken[2], Martin Sippel[2]

[1]Korea Aerospace Research Institute

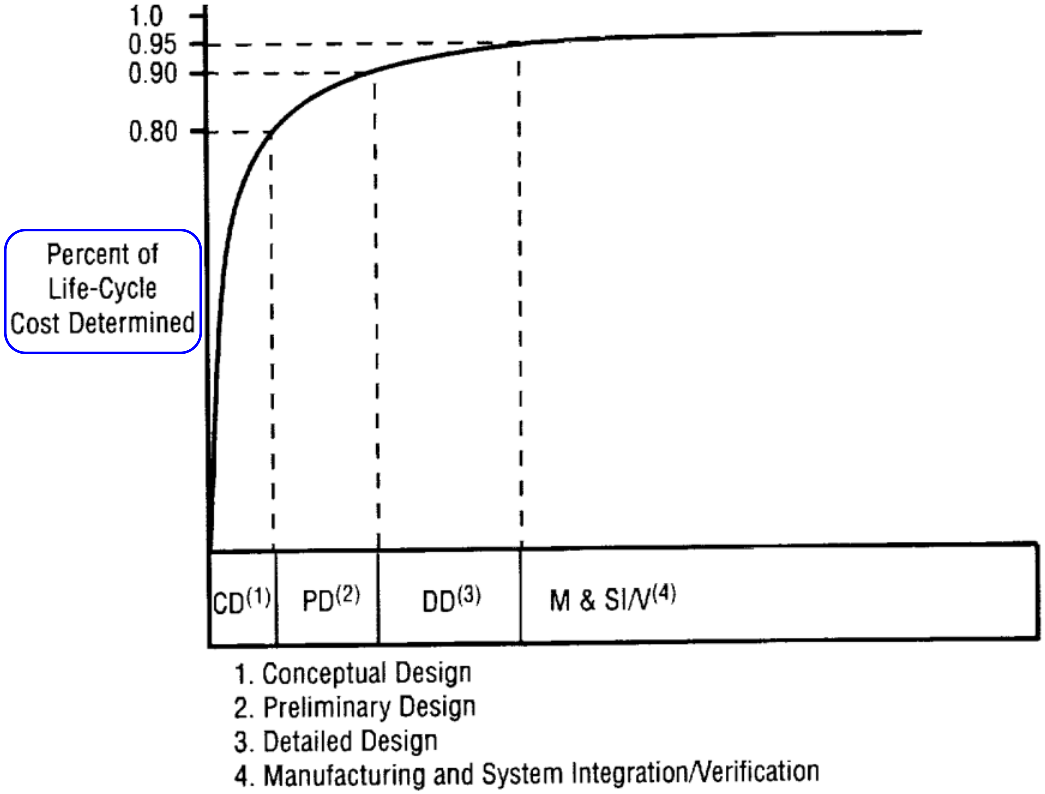
[2]German Aerospace Center

Contents

Cost

- Cost estimating is used for
  - Sizing your project office team
  - Affordability studies
  - …
- Why is cost estimating important?
  - Early-phase cost estimates are used in a decision-making for project feasibility.
  - Cost can be used as a design variable or objective for optimization.
    - ✓ Minimize cost or Maximize return
  - Most costs are frozen in early phase.

    → Early estimating is important.



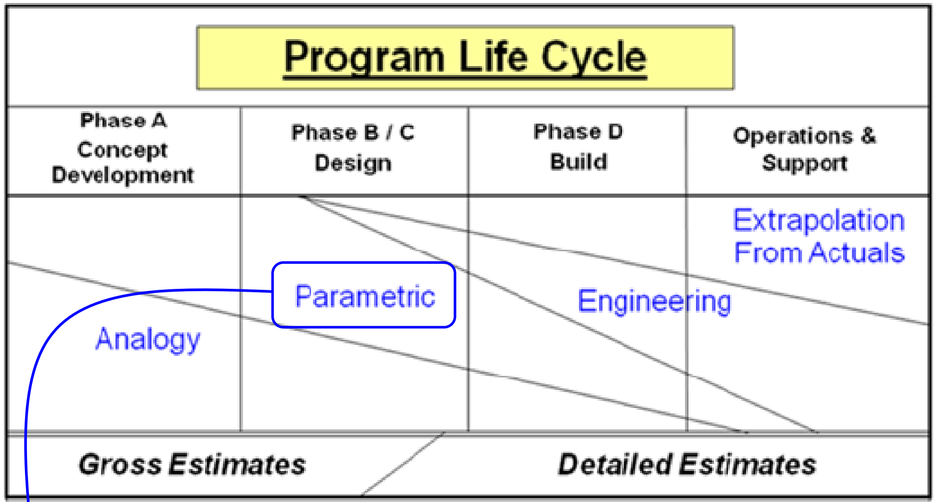
[1] J. C. Blair, Launch vehicle design process: characterization, technical integration, and lessons learned, NASA, 2001.

- Reasonable and transparent cost estimate is needed.

Contents

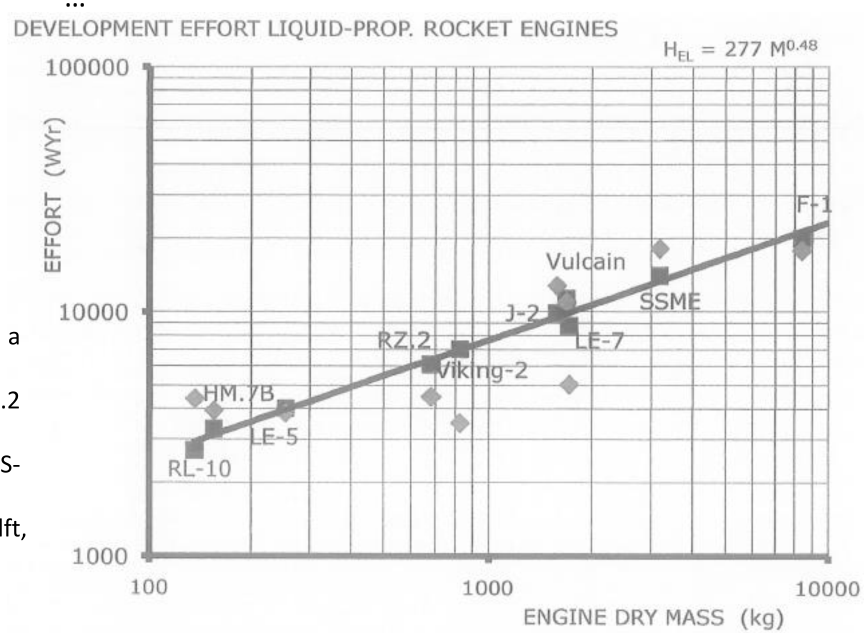
Cost estimation methods

- Methods



- Parametric method ($C = f(p_1, p_2, \dots, p_n)$)
  - Using the relationship between inputs & cost in previous programs
  - Usually mass is used as an input.

- Tools[2]
  - TransCost (Koelle)[3]
  - Unmanned Space Vehicle Cost Model (NASA)
  - Small Satellite Cost Model (NASA)
  - PCEC (NASA)[4]
  - SOLSTICE (ESA)[5]
  - SPICE 6 (ESA)
  - RACE (ESA)
  - TruePlanner (commercial)
  - SEER-H (commercial)
  - …



[2] Sang-Hyeon Choi, Nigel Drenthe, Keejoo Lee, and Seok-Hee Lim, "Cost Estimating for a SmallSat-Dedicated Launch Vehicle in Korea," in Space Cost Engineering Conference, 2021.
[3] D. Koelle, Handbook of cost engineering and design of space transportation systems, 8.2 edition, Ottobrunn Germany: TransCostSystems (TCS), 2013.
[4] "Business Systems And Project Management, Project Cost Estimating Capability (PCEC), MFS-33187-2," [Online]. Available: https://software.nasa.gov/software/MFS-33187-2.
[5] N. Drenthe, SOLSTICE: Small Orbital Launch Systems, a Tentative Initial Cost Estimate, TU Delft, 2016.

TransCost 8.2[3]

- Development cost

$C_D = f_0(\sum H_V + \sum H_E) f_6 f_7 f_8$ (WYr) : launch vehicle

$H_{VB} = 803.5 M_V^{0.385} f_1 f_2 f_3 f_8 f_{10} f_{11}$ (WYr) : reusable ballistic launch vehicle

$H_{VS} = 1113 M_V^{0.383} f_1 f_3 f_8 f_{10} f_{11}$ (WYr) : crewed space system

$H_E = 277 M_E^{0.48} f_1 f_2 f_3 f_8$ (WYr) : liquid-propellant rocket engine

- Manufacturing cost

$C_F = f_0^N(\sum F_V + \sum F_E) f_9$ (Wyr) : launch vehicle

$F_{VB} = 1.265 M_V^{0.59} f_4 f_8 f_{10} f_{11}$ (WYr) : reusable ballistic launch vehicle

$F_{VS} = 0.16 M_V^{0.98} f_4 f_8 f_{11}$ (WYr) : crewed space system

$F_E = 1.2 M_E^{0.535} f_4 f_8 f_{11}$ (WYr) : liquid-propellant rocket engine

f_0: system engineering/integration factor

f_1: technical development factor

f_2: technical quality factor

f_3: team experience factor

f_4: cost reduction factor by learning

f_6: cost growth factor for deviation from the optimum time schedule

f_7: cost growth factor for development by parallel contractors

f_8: country productivity factor

f_9: subcontractor cost factor

f_{10}: technical progress cost reduction factor

f_{11}: commercial factor

M_E: engine mass (kg)

M_V: dry mass of a vehicle without engines (kg)

N: number of stages

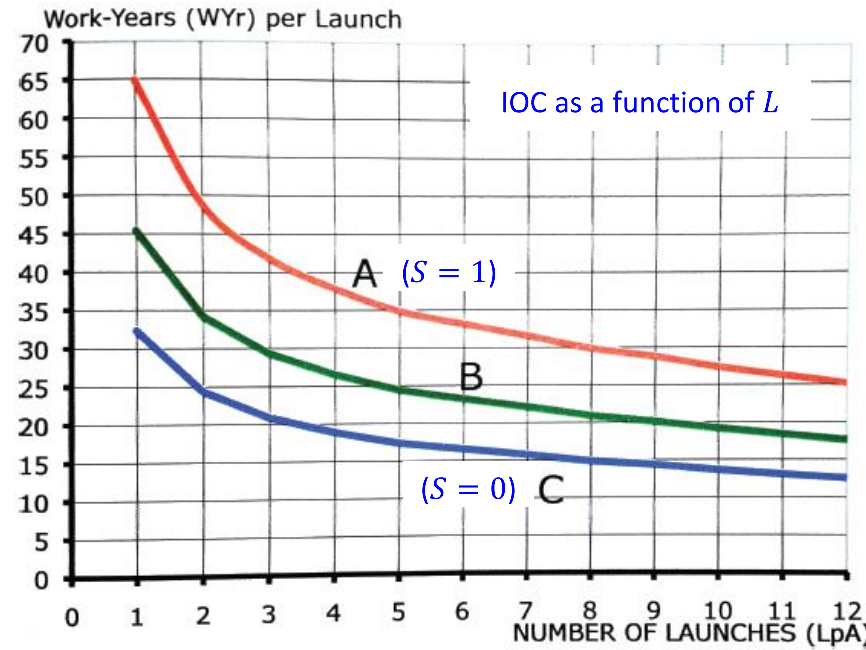
WYr: Work Year

[3] D. Koelle, Handbook of cost engineering and design of space transportation systems, 8.2 edition, Ottobrunn Germany: TransCostSystems (TCS), 2013.

TransCost 8.2

- Operating cost
  - Direct operating costs (DOC) - relating to launch itself
    - ✓ Ground operating cost: $C_G = 8M_0^{0.67}L^{-0.9}N^{0.7}f_v f_c f_4 f_8 f_{11}$ (WYr)
    - ✓ Propellant cost
    - ✓ Flight and mission operating cost
      - Launch vehicle: $C_M = 20(\sum Q_N)L^{-0.65}f_4 f_8$ (WYr)
      - Crewed vehicle: $C_{Mc} = 75T_m^{0.5}N_c^{0.5}L^{-0.8}f_4 f_8 f_{11}$ (WYr)
  - Indirect operating costs (IOC) - commercialization costs
    - ✓ $C_{IO} = (33S + 32)L^{-0.379}$ (WYr)

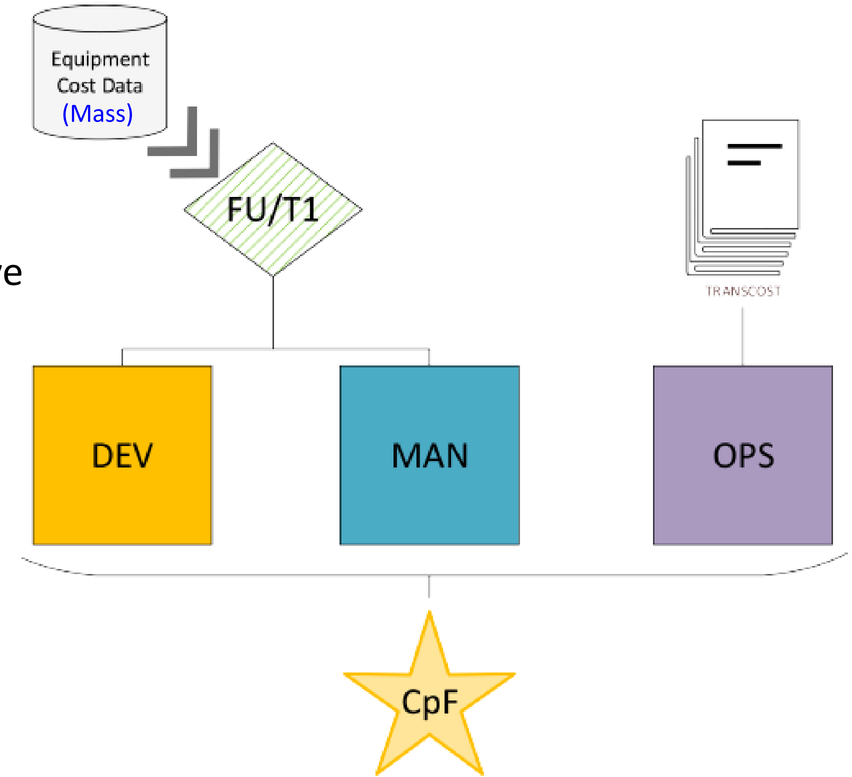
f_c: assembly and integration factor
f_v: vehicle type factor
L: number of launches per year
M_0: Gross Lift-Off Weight (GLOW) including payload (ton)
N_c: number of crew members
Q_N: vehicle complexity factor
S: percent of work subcontracted out
T_m: mission duration (days)



SOLSTICE[5]

- Small Orbital Launch Systems, a Tentative Initial Cost Estimate (SOLSTICE)
  - New method to estimate costs of small and commercial launch vehicles

- Five phase estimate
  ① T1 (Flight Unit cost)
    ✓ T1 = FM1 (Manufacturing) + Management + Product Assurance
    ✓ T1 = aM^b (k€)
  ② Development cost – Using T1
  ③ Manufacturing cost – Using learning curve
  ④ Operating cost – Using TransCost
  ⑤ Cost per Flight (CpF)



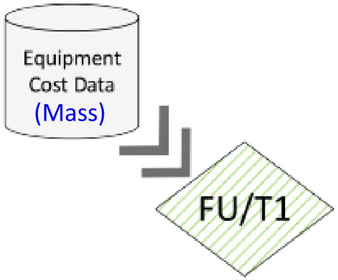
CpF estimating process

[5] N. Drenthe, SOLSTICE: Small Orbital Launch Systems, a Tentative Initial Cost Estimate, TU Delft, 2016.

SOLSTICE[5]

① T1 (Flight Unit cost)

- T1 = aM^b (k€)



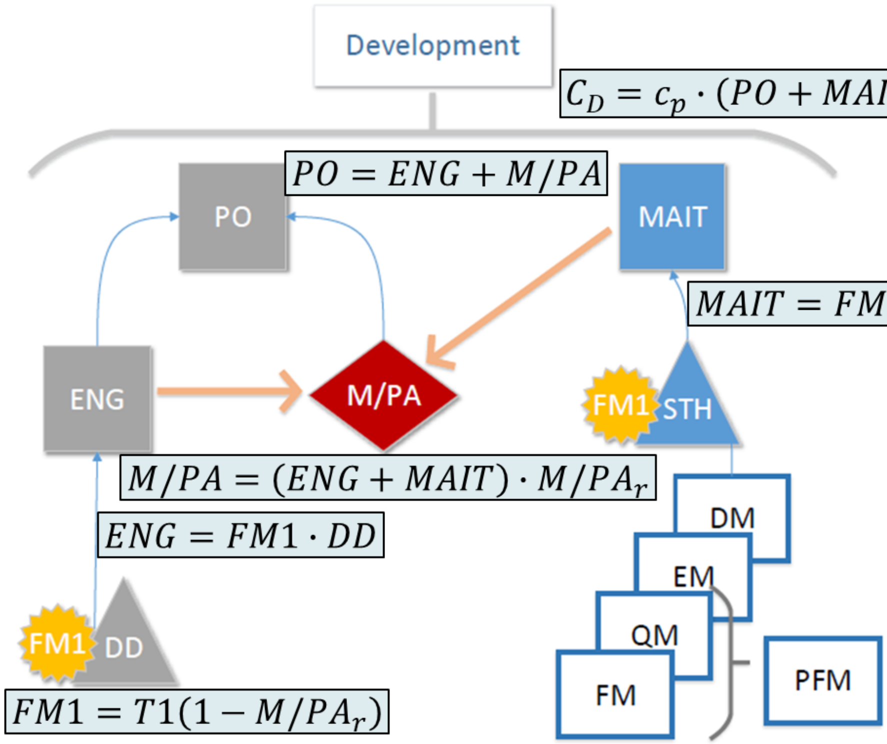
Equipment Element Name	Regression			NAFCOM		Used
	a value	*b* value	RSE/CMA	*a* value	*b* value	
Solid Casing, including solid propellant	90.72782	0.44422	12.9%	321.12767	0.30	Regression
Pressurizant Tank	19.99465	0.71253	27.6%	22.21748	0.70	Regression
Fuel Tank	19.99465	0.71253	27.6%	22.21748	0.70	Regression
Oxidizer Tank	19.99465	0.71253	27.6%	22.21748	0.70	Regression
Thrust Cone	2.79930	0.91199	12.6%	9.39259	0.70	Regression
Skirt	2.79930	0.91199	12.6%	9.39259	0.70	Regression
Thermal Control	2.79930	0.91199	12.6%	9.39259	0.70	Regression
Engine(s)	31.48271	0.78811	35.8%	322.07959	0.50	Regression
Thrust Vector Control	33.90978	0.60977	13.7%	35.44885	0.60	Regression
Pressurization System	11.50618	1.06948	49.8%	72.19775	0.60	Regression
Pipes	8.95877	0.68815	34.3%	8.96336	0.70	Regression
Valves	8.95877	0.68815	34.3%	8.96336	0.70	Regression
Stage Harness	27.45211	0.44623	34.9%	14.20721	0.75	Regression
Payload Adapter	124.86209	0.31031	13.0%	26.01794	0.70	Regression
Payload Fairing	4.09558	0.96587	9.2%	23.59239	0.70	Regression
Comms			*One data point only*	51.11253	0.80	NAFCOM
Power	56.13918	0.66916	*Two points*	42.01174	0.80	NAFCOM
Data Handling	141.82428	0.79249	16.3%	141.68203	0.80	Regression
GNC	69.05491	0.82458	23.8%	72.86034	0.80	Regression
Avionics Harness	27.45211	0.44623	34.9%	14.20721	0.75	Regression
Attitude Control Module	44.04074	1.06207	88.6%	257.84198	0.75	Regression
Interstage Structure	6.70369	0.68041	19.3%	6.16655	0.70	Regression

- SOLSTICE, PCEC: *can* estimate equipment elements' cost (bottom-up methods)
- TransCost: *cannot* estimate equipment elements' cost (top-down method)

[5] N. Drenthe, SOLSTICE: Small Orbital Launch Systems, a Tentative Initial Cost Estimate, TU Delft, 2016.

SOLSTICE[5]

② Development cost - Using T1



Development cost estimating process

c_p: cost reduction factor

DD: design and development T1 equivalent ($DD = 3 + \Delta TRL$)

ENG: engineering cost (k€)

$FM1$: flight unit manufacturing cost (k€)

L_d: learning factor for development costs

$MAIT$: manufacture, assembly, integration and test cost (k€)

M/PA: management and product assurance cost (k€)

M/PA_r: management and product assurance cost ratio

PO: project office cost (k€)

STH: System Test Hardware T1 equivalent

- DM (Development model): $STH = 0.3$
- EM (Engineering model): $STH = 1.3$
- QM (Qualification model): $STH = 1.3$
- PFM (Protoflight model): $STH = 1.5$
- FM (Flight model): $STH = 1$ (reference)

ΔTRL: change of technology readiness level during the development period

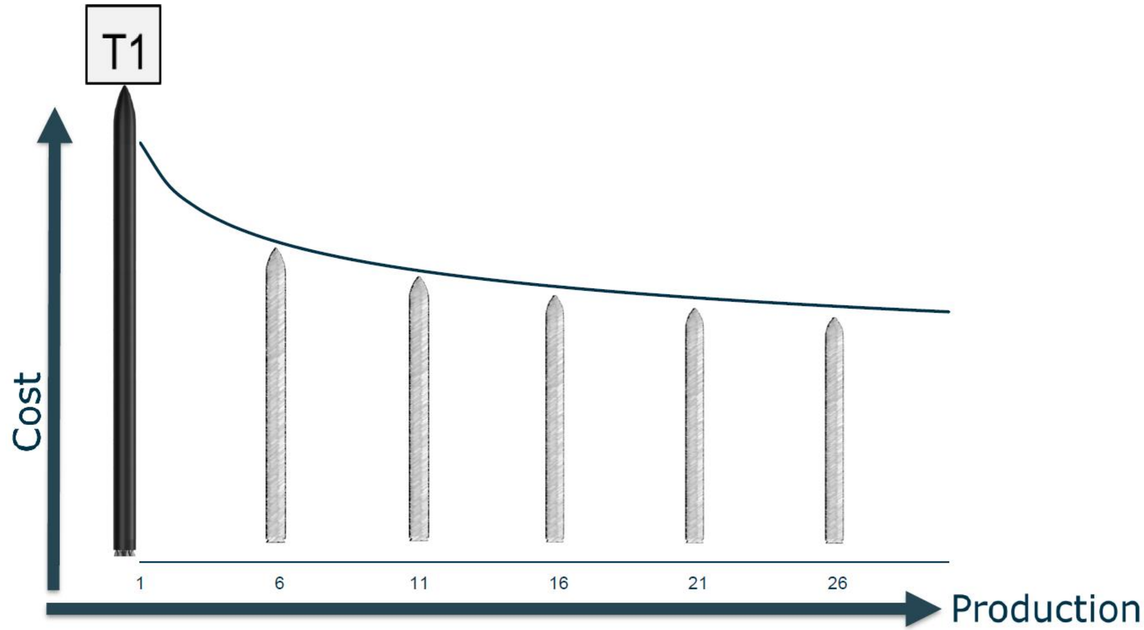
$\#HW$: number of hardware elements

[5] N. Drenthe, SOLSTICE: Small Orbital Launch Systems, a Tentative Initial Cost Estimate, TU Delft, 2016.

SOLSTICE[5]

③ Manufacturing cost – Using learning curve

- T1: First unit cost
- If hundreds are manufactured, you expect to see improvements in efficiency!



- Two typically applied learning curves:
  - ✓ Wright
  - ✓ Crawford (used in Drenthe's model)

$$n\text{-th unit cost: } C_N = T1 \cdot n^{\frac{ln(p)}{ln(2)}}$$

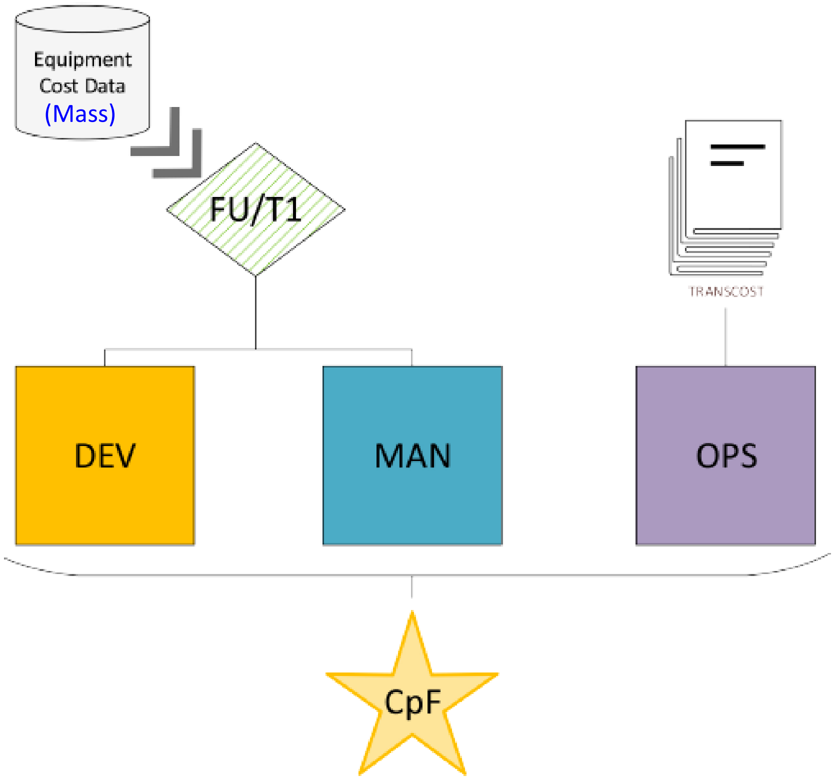
p: Cost improvement factor

[5] N. Drenthe, SOLSTICE: Small Orbital Launch Systems, a Tentative Initial Cost Estimate, TU Delft, 2016.

SOLSTICE

④ Operating cost – Using TransCost

⑤ Cost per Flight (CpF)



CpF estimating process

$$CpF = \frac{C_D}{N_a} + C_F + C_O$$

C_D: development cost of a launch vehicle

C_F: fabrication, assembly and test cost of a launch vehicle

C_O: operating cost of a launch vehicle

N_a: number of flights over which the development charge is spread

- DEV of the Falcon 1 was fully covered by NASA.

→ DEV should not be included in the CpF.

$$CpF = \cancel{\frac{C_D}{N_a}} + C_F + C_O$$

PCEC[4]

- Program Cost Estimating Capability (PCEC)
  - A primary staple of the NASA cost estimating tool suite over the past several decades: NAFCOM
  - After review, it was concluded that NAFCOM is not well-suited to adapt to the needs of NASA.

→ PCEC was developed by the MSFC Engineering Cost Office to address these challenges.

SOURCE DATABASES

- REDSTAR Library
- One NASA Cost Engineering (ONCE) Database

Cost Model Backup

- CASTS User's Guide - Restricted
- CASTS "Virtual Blackbooks"
- Robotic spacecraft data analysis spreadsheets and cost analysis reports*
- Cost Analysis Data Requirements (CADRe) documents

Accessible with NASA User ID and Account Approval

NASA IT Security Interface

PCEC COST MODELS

Launch Vehicles/Human Spaceflight Missions

- CASTS CERs
- CASTS User's Guide - Unrestricted

Robotic Science Missions

- Spacecraft Subsystem CERs
- PM/SE/MA/I&T CERs*
- NASA Instrument Cost Model

Estimating Support

- CER Library
- WBS Templates
- Help File
- Inflation Index
- Cost Phasing

Publically Releasable via NASA Software Release Authority Process

CER: Cost Estimating Relationship

[4] "Business Systems And Project Management, Project Cost Estimating Capability (PCEC), MFS-33187-2," [Online]. Available: https://software.nasa.gov/software/MFS-33187-2.

Contents

Investigation into Starship

- Launch rate[3]
  - Starship is expected to be able to launch up to three times per day.

First stage – Super Heavy	
Height	•70 m
Diameter	•9 m
Propellant mass	•3,400 t
Powered by	•Raptor engine (33)
Maximum thrust	•72 MN
Propellant	•liquid oxygen •liquid methane
Second stage – Starship	
Height	•50 m
Diameter	•9 m
Propellant mass	•1,200 t
Powered by	•Raptor engine (3) •Raptor Vacuum (3)
Propellant	•liquid oxygen •liquid methane

- Development cost
  - William Mook (2021)[6]: It will cost 22 B$ and take eight years to build the first real Starships.
  - Musk previously estimated that the company would cost around 5 B$ to complete.[7](2021)
  - Rich Smith (2022)[8]: Musk estimates it cost SpaceX only 2-4 B$ to develop Starship.

[3] D. Koelle, Handbook of cost engineering and design of space transportation systems, 8.2 edition, Ottobrunn Germany: TransCostSystems (TCS), 2013.
[6] "How much will it cost to build 1 starship?," Quora, [Online]. Available: https://www.quora.com/How-much-will-it-cost-to-build-1-starship. [Accessed 14 6 2023].
[7] "What's behind SpaceX's $74 billion valuation: Elon Musk's two 'Manhattan Projects'," CNBC, 19 2 2021. [Online]. Available: https://www.cnbc.com/2021/02/19/spacex-valuation-driven-by-elon-musks-starship-and-starlink-projects.html. [Accessed 14 6 2023].
[8] R. Smith, "You Won't Believe How Much It Will Cost for America to Return to the Moon," The Motley Fool, 19 3 2022. [Online]. Available: https://www.fool.com/investing/2022/03/19/how-much-will-americas-to-return-to-the-moon-cost/. [Accessed 14 6 2023].

Investigation into Starship costs

- Cost per Flight
  - Costs of Starship were estimated from the ITS costs.[9]
  - Cost of ITS have to be scaled down because
    - ✓ Starship had a smaller diameter of 9 m (instead of 12 m).
    - ✓ Also, the base structure of Starship is made of stainless steel instead of carbon fiber.

	ITS			Current		
	Booster	**Tanker**	**Starship**	**Booster**	**Tanker**	**Starship**
Manufacturing costs (US$)	230 M	130 M	200 M	122.36 M	68 M	107.4 M
Lifetime launches	1,000	100	12	100	100	10
Starts/Mars trip	6	5	1	5	4	1
Average maintenance costs/flight)	0.2 M	0.5 M	10 M	0.11 M	0.28 M	5.63 M
Propellant costs/launch (US$)	1.13 M	0.42 M	0.33 M	0.6 M	0.28 M	0.25 M
Launch site costs/launch (US$)	0.2 M			0.2 M		
Total costs/Mars trip (US$)	11 M	8 M	43 M	13 M	6 M	20 M

ITS: Interplanetary Transportation System

[9] Bjarne Westphala, Volker Maiwald, "Critical Analysis and Review of Current Mars Mission Scenarios for SpaceX Starship," in 73rd International Astronautical Congress, Paris, France, IAC-22-A5.2.3, 2022.

Cost estimation using TransCost - Dev. cost

- Development cost

1) $C_D = f_0(\sum H_V + \sum H_E) f_6 f_7 f_8$ (WYr) : launch vehicle

2) $H_{VB} = 803.5 M_V^{0.385} f_1 f_2 f_3 f_8 f_{10} f_{11}$ (WYr) : reusable ballistic launch vehicle

3) $H_{VS} = 1113 M_V^{0.383} f_1 f_3 f_8 f_{10} f_{11}$ (WYr) : crewed space system

4) $H_E = 277 M_E^{0.48} f_1 f_2 f_3 f_8$ (WYr) : liquid-propellant rocket engines with turbopumps

- Since 2nd stage of the Starship is a crewed vehicle, the development cost of 2nd stage was estimated using this equation.
- This equation may not be suitable because it is based on past systems that have characteristics different from Starship, such as Lunar lander, ISS Space station, and ISS-Columbus-Module.

Cost estimation using TransCost - Dev. cost

- Inputs for development cost

<table>
<tr><th colspan="2">Parameter</th><th>Value</th><th>Note</th></tr>
<tr><td colspan="2">M_{E1} (t)</td><td>3.2</td><td rowspan="2">Engine mass</td></tr>
<tr><td colspan="2">M_{E2} (t)</td><td>3.5</td></tr>
<tr><td colspan="2">N</td><td>2</td><td>Number of stages</td></tr>
<tr><td rowspan="4">f_1 (technical dev elopemnt factor)</td><td>f_{1_1V}</td><td>0.7</td><td>1st stage vehicle (Design modification of existing systems: 0.6-0.8)</td></tr>
<tr><td>f_{1_2V}</td><td>1.2</td><td>2nd stage vehicle (New design with some new technical and/or operational features: 1.1-1.2)</td></tr>
<tr><td>f_{1_1E}</td><td>0.7</td><td>1st stage engine (Design modification of existing systems)</td></tr>
<tr><td>f_{1_2E}</td><td>0.7</td><td>2nd stage engine (Design modification of existing systems)</td></tr>
<tr><td rowspan="2">f_2 (technical qual ity factor)</td><td>f_{2_1E}</td><td>0.73</td><td>1st stage engine; $f_2 = 0.26(lnN_Q)^2$
N_Q: number of qualification firings ($N_Q = 200$ [10])</td></tr>
<tr><td>f_{2_2E}</td><td>0.73</td><td>2nd stage engine</td></tr>
<tr><td rowspan="4">f_3 (team experie nce factor)</td><td>f_{3_1V}</td><td>0.8</td><td>1st stage vehicle (Team has performed development of similar projects: 0.7-0.9)</td></tr>
<tr><td>f_{3_2V}</td><td>0.8</td><td>2nd stage vehicle</td></tr>
<tr><td>f_{3_1E}</td><td>0.8</td><td>1st stage engine</td></tr>
<tr><td>f_{3_2E}</td><td>0.8</td><td>2nd stage engine</td></tr>
<tr><td colspan="2">f_6</td><td>1</td><td>Cost growth factor for deviation from the optimum time schedule
Assume meeting optimum time schedule</td></tr>
<tr><td colspan="2">f_7</td><td>1</td><td>Cost growth factor for development by parallel contractors: $f_7 = n_c^{0.2}$
$n_c = 1$ (n_c: number of participating parallel major contractors)</td></tr>
<tr><td colspan="2">f_8</td><td>1</td><td>Country productivity</td></tr>
<tr><td colspan="2">f_{10}</td><td>0.85</td><td>Technical progress cost reduction factor
$f_{10} = 0.85$ for SpaceLiner [11]</td></tr>
<tr><td colspan="2">f_{11}</td><td>0.55</td><td>Commercial factor (Table 5.2 of Ref. [5])</td></tr>
<tr><td colspan="2">$/WYr</td><td>371,559</td><td>Appendix C of Ref. [12] (FY2021)</td></tr>
<tr><td rowspan="3">1st stage</td><td>M_{n1} (t)</td><td>297.8</td><td>Vehicle dry mass (with residual propellant, w/o payload fairing)</td></tr>
<tr><td>M_{p1} (t)</td><td>3,400</td><td>Propellant mass</td></tr>
<tr><td>M_{V1} (t)</td><td>162.5</td><td>Vehicle dry mass (w/o engines)</td></tr>
<tr><td rowspan="3">2nd stage</td><td>M_{n2} (t)</td><td>157.7</td><td></td></tr>
<tr><td>M_{p2} (t)</td><td>1,200</td><td></td></tr>
<tr><td>M_{V2} (t)</td><td>107.1</td><td></td></tr>
<tr><td colspan="2">Payload (t)</td><td>163</td><td></td></tr>
</table>

Cost estimation using TransCost - Dev. cost

- Estimated dev. cost when crewed space systems CER was used for 2nd stage (FY2021)

Parameter		Value	Note
f_0		1.082	System engineering/integration factor (1.04^N)
f_{2_1V} (technical quality factor of 1st stage)	k_{ref1}	0.0901	From FIG. 2-36 of TransCost [3]
	k_{eff1}	0.0876	$k_{eff} = M_n/M_p$
	f_{2_1V}	1.0291	f_2 of 1st stage vehicle ($f_2 = k_{ref}/k_{eff}$)
Development cost of 1st stage	H_{V1}	21,955	WYr
	H_{E1}	5,652	WYr
	Dev. cost	29,860	WYr
		11.1	B$
Development cost of 2nd stage	H_{V2}	42,164	WYr
	Dev. cost	45,605	WYr
		16.9	B$
Development cost		75,465	WYr
		28.0	B$
		171,546	USD/kg

- Estimated dev. cost when reusable ballistic launch vehicles CER was used for 2nd stage (FY2021)

Parameter		Value	Note
f_0		1.082	Same as f_0 in left table
f_{2_1V}		1.0291	Same as f_{2_1V} in left table
f_{2_2V} (technical quality factor of 2nd stage)	k_{ref2}	0.1022	
	k_{eff2}	0.1314	
	f_{2_2V}	0.7777	f_2 of 2nd stage vehicle
Development cost of 1st stage	Dev. cost	29,860	WYr (Same as dev. cost in left table)
		11.1	B$ (Same as dev. cost in left table)
Development cost of 2nd stage	H_{V2}	24,226	WYr
	Dev. cost	26,203	WYr
		9.7	B$
Development cost		56,063	WYr
		20.8	B$
		127,443	USD/kg

[3] D. Koelle, Handbook of cost engineering and design of space transportation systems, 8.2 edition, Ottobrunn Germany: TransCostSystems (TCS), 2013.

Cost estimation using TransCost - Man. cost

- Manufacturing cost

1) $C_F = f_0^N(\sum F_V + \sum F_E) f_9$ (WYr) : launch vehicle

2) $F_{VB} = 1.265 M_V^{0.59} f_4 f_8 f_{10} f_{11}$ (WYr) : reusable ballistic launch vehicle

3) $F_{VS} = 0.16 M_V^{0.98} f_4 f_8 f_{11}$ (WYr) : crewed space system

4) $F_E = 1.2 M_E^{0.535} f_4 f_8 f_{11}$ (WYr) : modern liquid engines

- Inputs for manufacturing cost

Parameter	Value	Note
f_0	1.03	System engineering/integration factor f_0 is between 1.02 and 1.03, depending on the vehicle and program complexity (p.122 of TransCost [3])
f_4	1	Cost reduction factor
f_9 (subcontractor cost factor)	1	Refer to FIG. 2-68 of TransCost [3] Assume that Scope of Subcontracts = 0%
p	0.85	Cost improvement factor (Refer to Reference [11])

[3] D. Koelle, Handbook of cost engineering and design of space transportation systems, 8.2 edition, Ottobrunn Germany: TransCostSystems (TCS), 2013.
[11] T. Olga, Innovative Cost Engineering Approaches, Analyses and Methods Applied to SpaceLiner–an Advanced, Hypersonic, Suborbital Spaceplane Case-Study, Melbourne, Australia: PhD diss., Monash University, 2015.

Cost estimation using TransCost - Man. cost

- Estimated man. cost for 1st flight when crewed space systems CER was used for 2nd stage (FY2021)

Parameter		Value	Note
f_4 (cost reduction factor)	f_{4_1E}	0.56	Number of 1st stage engines = 33
	f_{4_2E}	0.78	Number of 2nd stage engines = 6 [13]
Manufacturing cost of 1st stage	F_{V1}	701.8	WYr
	F_{E1}	917.4	WYr
	Man. Cost	1,717.8	WYr
		638	M$
Manufacturing cost of 2nd stage	F_{V2}	6,354.1	WYr
	F_{E2}	241.8	WYr
	Man. Cost	6,997.6	WYr
		2,600	M$
Manufacturing cost		8,715.4	WYr
		3,238	M$

- Estimated man. cost for 1st flight when reusable ballistic launch vehicles CER was used for 2nd stage (FY2021)

Parameter		Value	Note
f_4 (cost reduction factor)	f_{4_1E}	0.56	Same as f_4 in left table
	f_{4_2E}	0.78	
Manufacturing cost of 1st stage		1,717.8	WYr (Same as the man. cost in left table)
		638	M$ (Same as the man. cost in left table)
Manufacturing cost of 2nd stage	F_{V2}	548.8	WYr
	F_{E2}	241.8	WYr (Same as F_{E2} in left table)
	Man. Cost	838.7	WYr
		312	M$
Manufacturing cost		2,556.5	WYr
		950	M$

[13] "SpaceX Starship," Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/SpaceX_Starship. [Accessed 14 6 2023].

Cost estimation using TransCost - Man. cost

- Estimated average man. cost for 1,000 flights when crewed space systems CER was used for 2nd stage (FY2021)

Parameter		Value	Note
f_4 (cost reduction factor)	f_{4_1V}	0.71	Number of 1st stage vehicles = 1,000/100 = 10 (Lifetime launches of booster: 100 [9]) Number of 1st stage engines = 33 X 10 = 330 [13] Number of 2nd stage vehicles = 1,000/10 = 100 (Lifetime launches of Starship: 10 [9]) Number of 2nd stage engines = 6 X 100 = 600 [13]
	f_{4_1E}	0.33	
	f_{4_2V}	0.44	
	f_{4_2E}	0.29	
Manufacturing cost of 1st stage	F_{V1}	499.4	WYr
	F_{E1}	547.9	WYr
	Man. Cost (new launcher)	1,111.0	WYr
		413	M$
	Man. Cost (average)	**6**	M$ (Refurbishment cost: 0.5%)
		12	M$ (Refurbishment cost: 2%)
Manufacturing cost of 2nd stage	F_{V2}	2,780.2	WYr
	F_{E2}	89.9	WYr
	Man. Cost (new launcher)	3,044.8	WYr
		1,131	M$
	Man. Cost (average)	**118**	M$ (Refurbishment cost: 0.5%)
		133	M$ (Refurbishment cost: 2%)
Manufacturing cost (new launcher)		4,155.9	WYr
		1,544	M$
Manufacturing cost (average)		**124**	M$ (Refurbishment cost: 0.5%)
		146	M$ (Refurbishment cost: 2%)

- Estimated average man. cost for 1,000 flights when reusable ballistic launch vehicles CER was used for 2nd stage (FY2021)

Parameter		Value	Note
f_4 (cost reduction factor)	f_{4_1V}	0.71	Same as f_4 in left table
	f_{4_1E}	0.33	
	f_{4_2V}	0.44	
	f_{4_2E}	0.29	
Manufacturing cost of 1st stage	(new launcher)	413	M$ (Same as the man. cost in left table)
	(average)	**6**	M$ (Refurbishment cost: 0.5%)
		12	M$ (Refurbishment cost: 2%)
Manufacturing cost of 2nd stage	F_{V2}	240.1	WYr
	F_{E2}	89.9	WYr (Same as F_{E2} in left table)
	Man. Cost (new launcher)	350.1	WYr
		130	M$
	Man. Cost (average)	**14**	M$ (Refurbishment cost: 0.5%)
		15	M$ (Refurbishment cost: 2%)
Manufacturing cost (new launcher)		1,461.1	WYr
		543	M$
Manufacturing cost (average)		**20**	M$ (Refurbishment cost: 0.5%)
		28	M$ (Refurbishment cost: 2%)

Cost estimation using TransCost - Operating cost

- Operating cost

$C_G = 8 M_0^{0.67} L^{-0.9} N^{0.7} f_v f_c f_4 f_8 f_{11}$ (WYr): ground operating cost

$C_{Mc} = 75 T_m^{0.5} N_c^{0.5} L^{-0.8} f_4 f_8 f_{11}$ (WYr): flight and mission operating cost of crewed vehicle

$C_{IO} = (33S + 32) L^{-0.379}$ (WYr): IOC

- Inputs for operating cost

Parameter	Value	Note
L	1,095	launches per year (three times per day [13])
M_0 (t)	5,160	Gross Lift-off Weight (GLOW)
N	2	Number of stages
f_4 for 1 flight	1	f_4: cost reduction factor by learning
f_4 for 1,000 flights	0.26	Cost improvement factor $p = 0.85$ (Reference [11])
f_8	1	Country productivity factor
f_c (assembly and integration factor)	0.85	Vertical assembly and checkout, transport to launch pad
f_v (vehicle type factor)	1.25	1st stage (automated cargo vehicles): f_v=0.7 2nd stage (crewed / piloted vehicles): f_v=1.8 $\rightarrow f_v$=(0.7+1.8)/2=1.25
$/WYr	371,559	Appendix C of Reference [12]
$/€	1.14	Reference [12]
Mixture ratio (O/F)	3.6	Reference [14]
LH4 cost per kg ($/t)	400	Reference [15]
LOX cost per kg ($/t)	160	
Total propellant mass (kg)	4,600	
Payload mass (ton)	163	
Specific Transportation Cost (€/kg)	5.84	Reference [12]
Payload site charge fee (€/kg)	6.00	
Public Damage Insurance (M€)	0.1	
Launch Site Fee (M$)	0.2	Reference [9]
T_m (days)	1	Mission duration (earth to earth transportation)
N_c	5	Number of crew members

Cost estimation using TransCost - Operating cost

- Calculated propellant mass and cost

		Value
Mass (t)	LCH4	1,000
	LOX	3,600
Propellant cost (M$)	LCH4	0.40
	LOX	0.58
	Total	0.98

- Estimated average operating cost (FY2021 M$)

	1 flight	1,000 flights	Note
(1) Ground Operations	1.59	0.41	
(2) Propellant Cost	0.98	0.98	From upper table
(3) Flight and Mission Operations	0.13	0.03	
(4) Transportation Costs	34.37	34.37	Using M_0 and specific transportation cost in the table on previous page
(5) Fees and Insurance Costs	1.43	1.43	Payload site charge fee + Public damage insurance + Launch site fee
(6) DOC	**38.50**	**37.22**	(1)+…+(5)
(7) IOC	**0.84**	**0.84**	Using thei IOC equation on previous page S (Percent of work subcontracted out)=0
Operating Cost	**39.34**	**38.06**	(6)+(7)

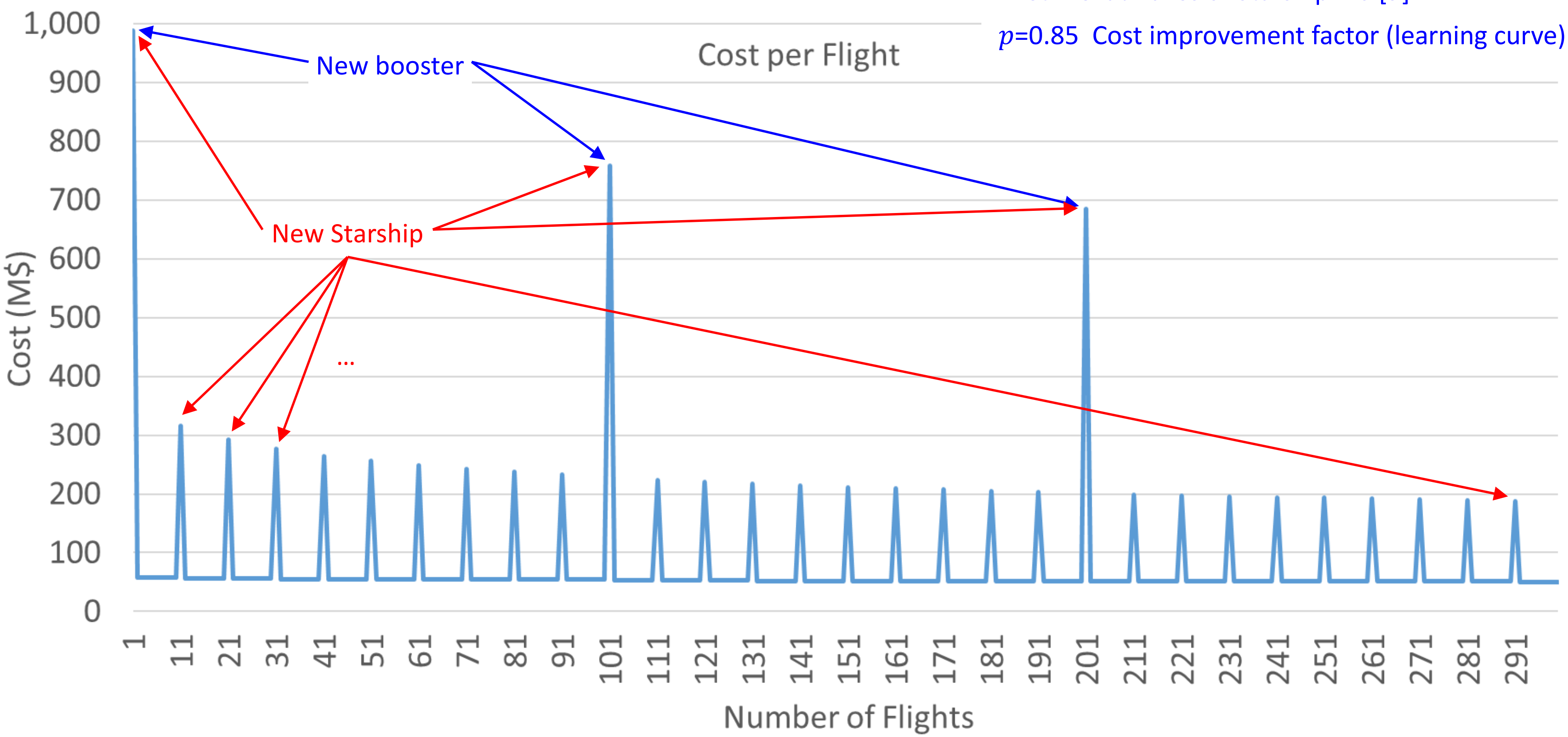
Cost estimation using TransCost - CpF

- Estimated CpF(Manufacturing Cost + Operating Cost) when reusable ballistic launch vehicles CER was used for Starship (FY2021, refurbishment cost: 2%)

Lifetime launches of booster: 100 [9]

Lifetime launches of Starship: 10 [9]

p=0.85 Cost improvement factor (learning curve) [11]



[9] Bjarne Westphala, Volker Maiwald, "Critical Analysis and Review of Current Mars Mission Scenarios for SpaceX Starship," in 73rd International Astronautical Congress, Paris, France, IAC-22-A5.2.3, 2022.

[11] T. Olga, Innovative Cost Engineering Approaches, Analyses and Methods Applied to SpaceLiner–an Advanced, Hypersonic, Suborbital Spaceplane Case-Study, Melbourne, Australia: PhD diss., Monash University, 2015.

Cost estimation using TransCost - CpF

- Estimated dev. cost and the average CpF (FY2021, refurbishment cost: 2%)

Costs	Crewed space systems CER		Reusable ballistic launch vehicles CER		Reference	Note
	1 flight	1,000 flights	1 unit	1,000 flights		
(1) Development Cost (M$)	28,040		20,831		22,000	[6]
Error	27%		-5%			
1st stage	11,095		11,095			
2nd stage	16,945		9,736			
(2) Manufacturing Costs (M$)	3,238	146	950	28		
(Manufacturing Costs)/CpF	99%	79%	96%	42%		(2)/(4)
1st stage	638	12	638	12	122.36	[9]
Error	422%		422%			
2nd stage	2,600	133	312	15	107.4	
Error	2321%		190%			
(3) Operating Cost (M$)	39	38	39	38		
	1%	21%	4%	58%		(3)/(4)
(4) CpF (M$)	**3,278**	**184**	**989**	**66**	33	(2)+(3) [9]
Error		457%		99%		

- Starship is a crewed system, but the estimated cost is too large when using a crewed model.
  - ✓ The estimate when using a reusable ballistic model is similar to the reference.
- Although the error in cost estimation is not small, the order of magnitude is the same.
- Estimated cost by TransCost is higher because data of traditional expensive launchers was used.

[6] "How much will it cost to build 1 starship?," Quora, [Online]. Available: https://www.quora.com/How-much-will-it-cost-to-build-1-starship.
[9] Bjarne Westphala, Volker Maiwald, "Critical Analysis and Review of Current Mars Mission Scenarios for SpaceX Starship," in 73rd International Astronautical Congress, Paris, France, IAC-22-A5.2.3, 2022.

Cost estimation using SOLSTICE

- Input values

Symbol	Parameter	Value	Note
M/PA_r	Management & Product Assurance contribution ratio	5.3%	Table 5.4 of Ref. [12]
DD_1	Design and Development T1 Equivalent (stage 1)	3	p.57 of Ref. [12]
DD_2	Design and Development T1 Equivalent (stage 2)	4	
STH	System Test Hardware T1 Equivalent	3.1	Table 5.4 of Ref. [12] (DM(0.3)+EM(1.3)+PFM(1.5))
L_{d2}	Development cost improvement/learning factor (n=2)	0.93	Cost improvement factor p = 0.85 [11] L_{dn}: average of $T1 \sim Tn$
L_{d4}	Development cost improvement/learning factor (n=4)	0.84	
L_{d6}	Development cost improvement/learning factor (n=9)	0.78	
L_{d33}	Development cost improvement/learning factor (n=9)	0.56	
c_p	Cost reduction factor	0.97	p.34, p.129 of of Ref. [5]

- Cost estimation for reusable hardware[12]
  - PCEC and adjustment factors based on data from past ESA missions are used.

Element	CER	AF
TPS	Thermal Protection System	3.5
Landing Legs	Recovery Systems	0.2
Parachute	Recovery Systems	0.6
Grid Fin	Mechanisms-Other	0.0013135

Table 4.2: Adjustment Factors developed for use with CASTS CERs, based on ESA data.

[5] N. Drenthe, SOLSTICE: Small Orbital Launch Systems, a Tentative Initial Cost Estimate, TU Delft, 2016.
[11] T. Olga, Innovative Cost Engineering Approaches, Analyses and Methods Applied to SpaceLiner–an Advanced, Hypersonic, Suborbital Spaceplane Case-Study, Melbourne, Australia: PhD diss., Monash University, 2015.
[12] G. Vera-Cruz, Reliability and Cost Modeling of Reusable Launch Vehicles: Predicting, Preventing and Mitigating the Cost of Failure, TU Delft, 2022.

Comparison between estimated results and reference values

- Estimated development cost and the average CpF (FY2021, refurbishment cost: 2%)

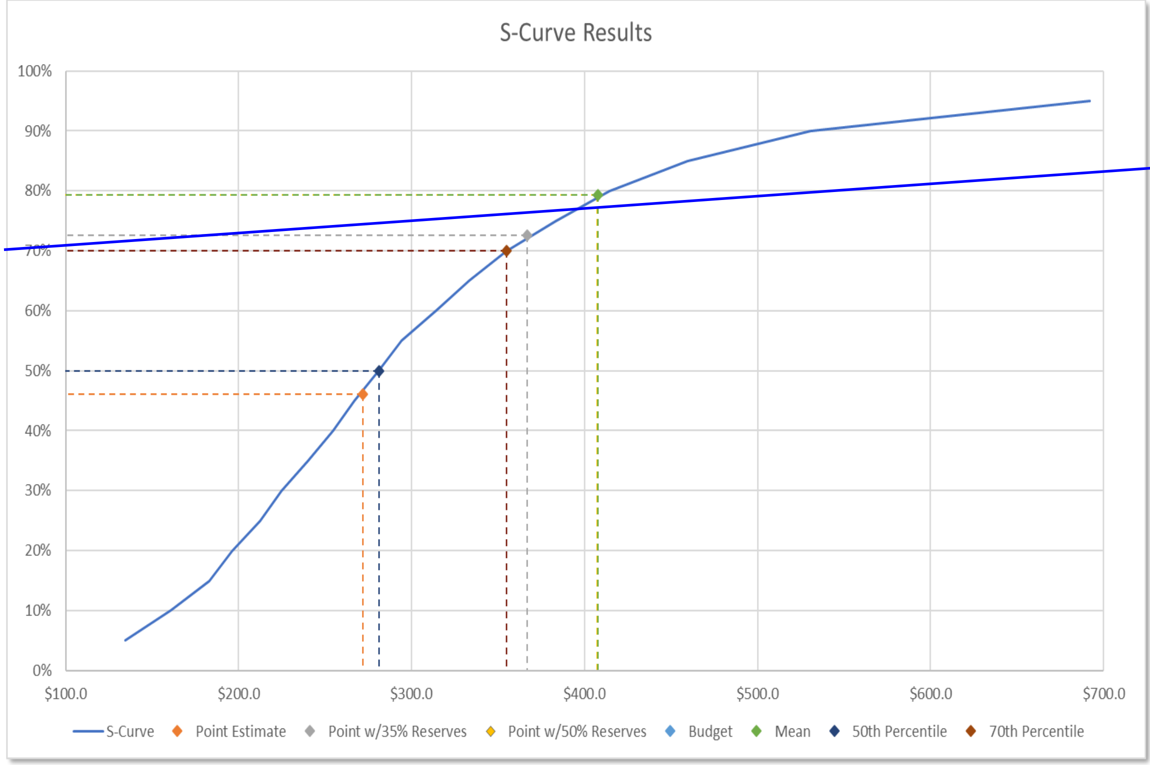
Costs	TransCost 8.2						SOLSTICE			PCEC			Reference	Note
	Crewed space systems model			Reusable ballistic launch vehicles model										
	1 flight	1,000 flights		1 flight	1,000 flights		1 flight	1,000 flights		1 flight	1,000 flights			
		New launcher	Average		New launcher	Average		New launcher	Average		New launcher	Average		
(1) Development Costs (M$)	28,040			20,831			10,350			37,582			22,000	[6]
Error	27%			-5%			-53%			71%				
1st stage	11,095			11,095			4,936			21,327				
2nd stage	16,945			9,736			5,414			16,255				
(2) Manufacturing Costs (M$)	3,238	1,544	146	950	543	28	2,099	1,328	63	5,095	3,221	153		
(Manufacturing Costs)/CpF	99%	98%	79%	96%	93%	42%	98%	97%	62%	99%	99%	80%		(2)/(4)
1st stage	638	413	12	638	413	12	1,495	1,064	32	3,618	2,574	77	122.36	
Error	422%			422%			1122%			2857%				
2nd stage	2,600	1,131	133	312	130	15	603	264	31	1,478	646	76	107.4	[9]
Error	2321%			190%			462%			1276%				
(3) Operating Cost (M$)	39	38	38	39	38	38	39	38	38	39	38	38		
	1%	2%	21%	4%	7%	58%	2%	3%	38%	1%	1%	20%		(3)/(4)
(4) CpF (M$)	**3,278**	**1,582**	**184**	**989**	**581**	**66**	**2,138**	**1,366**	**101**	**5,134**	**3,259**	**191**	33	(2)+(3) [9]
Error			457%			99%			206%			479%		

- Results estimated by TransCost using reusable ballistic launch vehicles CER were more similar to the reference values than those estimated using SOLSTICE or PCEC.
- Results estimated by PCEC were much larger than those estimated by TransCost or SOLSTICE.
  - ✓ Additional research on adjustment factors should be conducted.

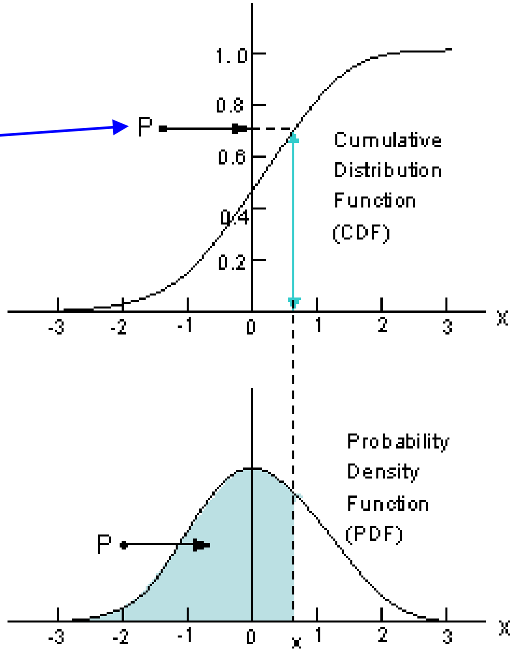
Cost estimation using PCEC - Uncertainty analysis

- Options (PCEC v2.3 Help.pdf)
  - Calculation mode: CER Uncertainty Only
  - Sampling: Monte Carlo Sampling, Trials per simulation = 1000
  - Distribution: Student's T-distribution

- Results (development cost of Stg1 - Thrust Structure)



P is the probability that X is less than x.



Relations Between Two Different Typical Representations of a Population

Contents

Conclusion

- Starship is a crewed system, but the estimated cost is too large when using a crewed space systems CER.
  - It may not be suitable for estimating the cost of Starship because it is a CER created based on past systems that have characteristics different from Starship, such as Lunar lander, ISS Space station, and ISS-Columbus-Module.
- The results estimated by TransCost using reusable ballistic launch vehicles CER were more similar to the reference values than those estimated using SOLSTICE or PCEC.
- And the results estimated by PCEC were much larger than those estimated by TransCost or SOLSTICE.
  - Additional research on adjustment factors should be conducted to increase the reliability of the results estimated using PCEC.

Thank you for your attention!

If you have any questions, please ask them now or send me (shchoi@kari.re.kr) an email.
I will answer your questions as soon as possible.

References

[1] J. C. Blair, Launch vehicle design process: characterization, technical integration, and lessons learned, NASA, 2001.

[2] Sang-Hyeon Choi, Nigel Drenthe, Keejoo Lee, and Seok-Hee Lim, "Cost Estimating for a SmallSat-Dedicated Launch Vehicle in Korea," in Space Cost Engineering Conference, 2021.

[3] D. Koelle, Handbook of cost engineering and design of space transportation systems, 8.2 edition, Ottobrunn Germany: TransCostSystems (TCS), 2013.

[4] "Business Systems And Project Management, Project Cost Estimating Capability (PCEC), MFS-33187-2," [Online]. Available: https://software.nasa.gov/software/MFS-33187-2.

[5] N. Drenthe, SOLSTICE: Small Orbital Launch Systems, a Tentative Initial Cost Estimate, TU Delft, 2016.

[6] "How much will it cost to build 1 starship?," Quora, [Online]. Available: https://www.quora.com/How-much-will-it-cost-to-build-1-starship. [Accessed 14 6 2023].

[7] "What’s behind SpaceX’s $74 billion valuation: Elon Musk’s two ‘Manhattan Projects’," CNBC, 19 2 2021. [Online]. Available: https://www.cnbc.com/2021/02/19/spacex-valuation-driven-by-elon-musks-starship-and-starlink-projects.html. [Accessed 14 6 2023].

[8] R. Smith, "You Won't Believe How Much It Will Cost for America to Return to the Moon," The Motley Fool, 19 3 2022. [Online]. Available: https://www.fool.com/investing/2022/03/19/how-much-will-americas-to-return-to-the-moon-cost/. [Accessed 14 6 2023].

[9] Bjarne Westphala, Volker Maiwald, "Critical Analysis and Review of Current Mars Mission Scenarios for SpaceX Starship," in 73rd International Astronautical Congress, Paris, France, IAC-22-A5.2.3, 2022.

[10] "SpaceX on Twitter: "If 200 Falcon second stage vehicles and Merlin Vacuum engines weren’t enough for you, the Raptor team recently completed the 200th Raptor 2 engine!"," reddit, 2022. [Online]. Available: https://www.reddit.com/r/spacex/comments/ym3nqj/spacex_on_twitter_if_200_falcon_second_stage/. [Accessed 15 6 2023].

[11] T. Olga, Innovative Cost Engineering Approaches, Analyses and Methods Applied to SpaceLiner–an Advanced, Hypersonic, Suborbital Spaceplane Case-Study, Melbourne, Australia: PhD diss., Monash University, 2015.

[12] G. Vera-Cruz, Reliability and Cost Modeling of Reusable Launch Vehicles: Predicting, Preventing and Mitigating the Cost of Failure, TU Delft, 2022.

[13] "SpaceX Starship," Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/SpaceX_Starship. [Accessed 14 6 2023].

[14] "SpaceX Raptor," Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/SpaceX_Raptor. [Accessed 16 6 2023].

[15] B. Wang, "SpaceX Reusable Rocket Costs Versus Airplanes," Next Big Future, 11 2 2022. [Online]. Available: https://www.nextbigfuture.com/2022/02/spacex-reusable-rocket-costs-versus-airplanes.html. [Accessed 14 6 2023].