

Estimating the Life Cycle Cost of Space Systems

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A space system's Life Cycle Cost (LCC) includes design and development, launch and emplacement, and operations and maintenance. Each of these cost factors is usually estimated separately. NASA uses three different parametric models for the design and development cost of crewed space systems; the commercial PRICE-H space hardware cost model, the NASA-Air Force Cost Model (NAFCOM), and the Advanced Missions Cost Model (AMCM). System mass is an important parameter in all three models. System mass also determines the launch and emplacement cost, which directly depends on the cost per kilogram to launch mass to Low Earth Orbit (LEO). The launch and emplacement cost is the cost to launch to LEO the system itself and also the rockets, propellant, and lander needed to emplace it. The ratio of the total launch mass to payload mass depends on the mission scenario and destination. The operations and maintenance costs include any material and spares provided, the ground control crew, and sustaining engineering. The Mission Operations Cost Model (MOCM) estimates these costs as a percentage of the system development cost per year.

Nomenclature

<i>ALS</i>	=	Advanced Life Support
<i>AMCM</i>	=	Advanced Missions Cost Model
<i>ASTP</i>	=	Advanced Space Transportation Program
<i>BVAD</i>	=	Baseline Values and Assumptions Document
<i>CEH</i>	=	Cost Estimating Handbook
<i>CER</i>	=	Cost Estimating Relationship
<i>DDT&E</i>	=	Design, Development, Test, and Evaluation
<i>ECLS</i>	=	Environmental Control and Life Support
<i>IOC</i>	=	Initial Operation Capability
<i>ISS</i>	=	International Space Station
<i>JSC</i>	=	Johnson Space Center
<i>L&E</i>	=	Launch and Emplacement
<i>LCC</i>	=	Life Cycle Cost
<i>LEO</i>	=	Low Earth Orbit
<i>LSS</i>	=	Life Support Systems
<i>MOCM</i>	=	Mission Operations Cost Model
<i>MSFC</i>	=	Marshall Space Flight Center
<i>NAFCOM</i>	=	NASA-Air Force Cost Model
<i>PCEC</i>	=	Project Cost Estimating Capability
<i>PRICE</i>	=	Parametric Review of Information for Costing and Evaluation
<i>SLS</i>	=	Space Launch System
<i>SOCM</i>	=	Space Operations Cost Model
<i>SVLCM</i>	=	Spacecraft/Vehicle Level Cost Model
<i>TRL</i>	=	Technology Readiness Level
<i>WBS</i>	=	Work Breakdown Structure

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I. Introduction

THIS report considers how to estimate the Life Cycle Cost (LCC) of space systems. The LCC contains all the costs of a project, program, or mission. LCC has three components, Design, Development, Test, and Evaluation (DDT&E), Launch and Emplacement (L&E), and Operations. These are usually estimated separately.

LCC is a basic metric in systems engineering and is fundamental in NASA planning. An understanding of expected costs is needed to help select technology and compare design architectures and mission scenarios. LCC should be considered in trade studies and design change proposals. (NASA Systems Engineering Handbook 2007, p. 119)

A. Cost estimation and control

The LCC can be used to define the project cost profile or set an overall cost cap. It follows that estimating the LCC correctly in detail and over time is highly desirable. (NASA Systems Engineering Handbook, 2007, pp. 125-129) The cost estimating methods described in this paper are logical, well established, and generally accepted. They are usually thought to be correct and useful. Nevertheless, frequent substantial cost overruns show that accurately estimating and controlling project cost is not a solved problem. Estimating and controlling cost is technically difficult, but the major problem is that human political and personal interests prevent us from making good cost estimates and keeping costs within planned limits.

B. Human behavioral problems that affect cost estimation and control

Some of the human behavioral problems with costs include the use of best-case minimum cost estimates, political sensitivity to high cost estimates, short term rather than long term or life cycle thinking, and failure to ignore sunk costs.

1. *Best case cost estimates*

The cost estimates that are presented to secure project approval tend to be the best-case minimum cost, to be optimistic, and to have no contingency reserve. Predicting cost is one of the many forms of predicting the future. Most future predictions are not really intended to be accurate. They are often disguised advocacy of some project or action. Cost estimates can be improved using actual cost data, tracking prediction performance, and identifying and minimizing the sources of error. Cost estimates should be made by independent analysts and not influenced by project advocates or opponents.

2. *Political sensitivity to costs*

The key activity in NASA or any project organization is selecting and funding projects. Cost estimates enter into the trade-offs and directly affect project approval. Budget estimates are usually challenged and revised during bureaucratic funding struggles.

It is politically astute to avoid premature discussion or estimation of costs. For example,

“NASA has not released comprehensive, long-term cost estimates for SLS and Orion. The reason is to avoid giving Congress sticker shock, said William Gerstenmaier, NASA’s associate administrator for human exploration and operations. “If we laid out a path directly to Mars and we laid out all the vehicles and all the testing and all the work to get there, then you end up with a fairly long period of time with a lot of funding that goes into that activity that says this program is something maybe we don’t want to go do,” Gerstenmaier said in November during a panel discussion with SLS and Orion prime contractors at the Newseum in Washington.” (Leone 2014)

3. *Short term rather than long term or life cycle thinking*

Short term thinking can be described as overly discounting the future. In financial planning, future costs and benefits should be discounted back to their current present value. Since money earns interest, a dollar today is worth more than a dollar in ten years. It will amount to the original dollar plus the accumulated compound interest. The selection of any particular interest or discount rate is somewhat arbitrary but it strongly affects the expected financial return of investments. The Office of Management and Budget long ago mandated a very high discount rate of 10% for federal projects. (de Neufville 1990) (OMB 1992) The present value of one dollar received in ten years is only 39 cents today at a 10% discount rate. If 39 cents is placed at 10% compound interest, it will amount to one dollar in ten years. For an investment to be profitable at a high 10% discount rate, 39 cents we spend today must pay back more than a dollar in ten years. If interest rates are high, only high return investments can make a profit.

Current interest rates for government bonds are nominally about 2%. Since inflation is also about 2%, the real interest rate, defined as the nominal interest rate minus inflation, is roughly zero. This means that a future dollar to be received ten years from now is worth about as much as a dollar on hand now. We can spend much more than 39 cents, we can spend nearly a full dollar, to get back a dollar ten years in the future. The current near zero interest rate is quite unusual and is the intended effect of the government providing money to stimulate the economy. The US should take advantage of the current low interest rate by investing more heavily in infrastructure – roads, bridges,

airports - and in research and development - biotech, automation, energy, space. Low interest rates discourage saving and stimulate investment, at least for rational long term optimizers.

Most individuals do not plan their personal finance based on the available interest rate. People have compelling current needs and limited current income, so they often borrow at high rates. Individuals subjectively perceive a high interest rate. To most of us, a dollar now seems much more valuable than a dollar in the far future. Most save little for retirement.

Project managers also seem to intuitively use the same high interest rate as most private individuals. They tend to spend all available dollars to solve current problems with no goal beyond delivering a working product on schedule. Project managers under budget and schedule pressure tend not to invest in the better reliability, operability, and maintainability that would reduce overall Life Cycle Cost.

An organization such as NASA can mandate the goal of reducing LCC, but directives have limited ability to affect the detailed investment decisions made in a project. Ed Smiley, of Apollo 13 rescue fame, told me "We never considered operations costs" in response to a presentation advocating LCC. (Smiley 2003)

4. Not ignoring sunk costs

A sunk cost is a past cost that has already been incurred and cannot be recovered. In economic theory, only future costs and benefits should be relevant to current investment decisions. Letting past sunk costs influence future spending is irrational. However, humans usually have professional, personal, and project commitments that make them very reluctant to admit failure and terminate an unsuccessful project.

Past investments were made to produce our current knowledge and technology options. Past expenses can never be unspent. The current technical possibilities, not past hopes or sunk costs, should determine future funding decisions. In practice, sunk costs are often not ignored. Saving face, maintaining commitment, and establishing credibility can block the economically rational choice.

Regardless of these human problems, it is necessary to better understand, correctly estimate, and effectively control costs. Improvement is possible and urgently needed.

The LCC has three components, DDT&E, L&E, and Operations. DDT&E cost estimation is considered first.

II. Design, Development, Test, and Evaluation (DDT&E) cost estimation

The costs for a new system design, development, test, and evaluation are often estimated top-down, using parametric cost estimating relationships derived from similar hardware. The major cost driver for space systems is weight. A first approximation of flight hardware cost is some factor times the component weight to some power, such as $\text{factor} * (\text{weight})^x$. The exponent of weight, x , is typically about 0.5, and ranges from 0.25 to 0.75, so cost increases more slowly than weight. Large adjustments to the estimated costs are usually made on the basis of estimated system complexity.

An alternate approach is to estimate the costs bottom-up, by summing the estimated costs of hardware design, development, and test. A bottom-up estimate seems more convincing than a top-down estimate because it can be justified in detail, but it is usually more subjective and less accurate. Detailed engineering cost summations can be useful for existing systems but can be far off for new systems. Cost estimators strongly prefer top-down cost estimates.

Parametric cost models provide the most effective way to estimate the DDT&E cost of space hardware early in the mission cycle. NASA uses three different parametric models for crewed space systems; the Advanced Missions Cost Model (AMCM), the commercial PRICE-H space hardware cost model, and the NASA-Air Force Cost Model (NAFCOM). The Spacecraft/Vehicle Level Cost Model (SVLCM) estimates spacecraft costs only. The Project Cost Estimating Capability (PCEC) has been developed to replace NAFCOM.

A. The Advanced Missions Cost Model (AMCM).

The AMCM was developed by the Exploration Programs Office at Johnson Space Center. It was intended to be a long-range cost forecasting tool that could predict cost as far out as 25 to 50 years, that would include substantially different types of systems, would be simple to use, would require few inputs, and would allow cost studies to be performed quickly and efficiently during the early conceptual stages of a mission.

The model parameters include all the major cost drivers. The user defined inputs include the system dry mass, the total quantity of development and production units, the type of mission, the first year of system operations, the hardware block or generation, and the estimated difficulty. Design cost economies of scale occur with mass for most development hardware. The learning curve gives production economies of scale for an increasing number of units. The type of mission is related to organizational cultural differences that affect cost. Spacecraft, missiles, aircraft, ships, and ground mobile equipment have decreasing costs. The cost of programs has increased with time, even after

the effects of inflation are accounted for. The future mission time allows long range planning. Using existing designs provides substantial reductions in cost. The estimated difficulty accounts for differences in performance, capacity, readiness of technology, and complexity of design.

The AMCM data base includes eight manned spacecraft developed by NASA; Mercury, Gemini, Apollo command module, Apollo lunar module, skylab, shuttle orbiter, spacelab, and station. The overall database has more than 260 development programs. Historical cost data is normalized by systematically accounting for the effects of different initial operating dates, quantities, and weights. (Cyr 1988) (Guerra and Shishko 2000, pp. 946-7)

The AMCM is a single Cost Estimating Relationship (CER) using mass, quantity, mission type, number of design generations, and technical difficulty to estimate the total system cost for DDT&E and production.

The AMCM formula for the cost of DDT&E and production in millions of 1999 dollars is:

$$\text{Development and production cost} = \alpha Q^{\beta} M^{\Xi} S^{\sum} \sum^{1/(IOC - 1900)} B^{\Psi} \odot^D$$

The Greek letter constants are:

$$\alpha = 5.65 \times 10^{-4}$$

$$\beta = 0.5941$$

$$\Xi = 0.6604$$

$$\sum = 80.599$$

$$\sum = 3.8085 \times 10^{-55}$$

$$\Psi = -0.3553$$

$$\odot = 1.5691$$

Substituting approximately for the constants, the AMCM becomes

$$\text{Development and production cost} = 5.65 \times 10^{-4} Q^{0.59} M^{0.66} 80.6 S^{\sum} (3.81 \times 10^{-55})^{1/(IOC - 1900)} B^{-0.36} 1.57^D$$

Q is the total quantity of development and production units, M is the system dry mass in pounds, S specifies the type of mission (2.13 for human habitat, 2.46 for crewed planetary lander), IOC (Initial Operation Capability) is the first year of system operations, B is the hardware block or generation (1 for new design, 2 for second generation), and D is the estimated difficulty (0 for average, 2.5 for extremely difficult, and -2.5 for extremely easy). (Guerra and Shishko 2000, pp. 946-7)

The AMCM is available online (Federation of American Scientists 2014). It has been applied to life support systems in (Jones 2013-3407) and (Jones 2012-3618).

1. AMCM parameters and their effects

The AMCM model uses well established cost drivers. Cost per unit decreases with the quantity of units, Q, due to the effect of experience reflected in the learning curve. Q includes development units, credit for partial units and mock-ups, test units, and flight units. The dry mass, M, is the most frequently used cost estimation parameter. M is here in pounds. For kilograms, $\alpha = 9.51 \times 10^{-4}$. Different types of missions have had very different costs per unit weight. The type of mission, S, allows the AMCM formula to be used for the major different missions. The year of Initial Operation Capability, IOC, accounts for the fact that the cost of programs increases with time. The hardware block or number of past generations, B, reflects that cost decreases with the level of design inheritance. The most subjective parameter in AMCM is the difficulty, D. Adjustments for difficulty or complexity are also used in the PRICE and NAFCOM models. The difficulty parameter can reflect differences in technology, materials, manufacturing processes, parts count, design inheritance, schedule, the number of different organizations involved, and even the developing organization's experience and culture. (Guerra and Shishko 2000, pp. 946-947) The FY1999 dollars are usually adjusted to current dollars using inflation tables.

Table 1 shows the AMCM cost estimate for a reference system with Q = 1, M = 100, S = 2.13 for a human habitat, IOC = 2015, B = 1, and D = 0, and for variations of each parameter.

Table 1. AMCM cost estimates for a reference system and variations of each parameter.

Parameter		Values							
Q	Quantity	1	2	1	1	1	1	1	1
M	Mass	100	100	200	100	100	100	100	100
S	Specification	2.13	2.13	2.13	2.46	2.13	2.13	2.13	2.13
IOC	Initial date	2015	2015	2015	2015	2025	2015	2015	2015
B	Block	1	1	1	1	1	2	1	1
D	Difficulty	0	0	0	0	0	0	-2.5	+2.5
Total cost, M\$		46	69	72	195	50	36	15	141
Unit cost ratio		1.00	0.75	1.58	4.26	1.09	0.78	0.32	3.08

The estimated cost is 46 million 1999 dollars for a 100 pound unit. Variations of each parameter are shown in bold. For two units, $Q = 2$, the total cost increases only by 50% and the cost per unit decreases by 25%. Doubling the mass, M , increases unit cost by 58% but the cost per kilogram is 21% less. If the mission specification, S , is 2.46 for crewed planetary lander, the total cost is 4.26 times higher, 195 million 1999 dollars. If the IOC date is 2025 instead of 2015, cost increases only 9%. For a second generation block $B = 2$ instead of 1, the cost is 22% less. For an extremely easy development with a difficulty, $D = -2.5$, cost decreases by a factor of 3. For an extremely difficult development, $D = -2.5$, cost is 3.08 times higher.

2. AMCM cost estimates

The development and production cost for human space missions typically has been \$50 to 150 k/kg. (Wertz and Larson 1996, p. 254) (National Academy Press, App. C 1997) (Guerra and Shishko 2000, p. 953)

Consider a development similar to the International Space Station (ISS) life support system. Suppose $Q = 1$, $M = 1,500$ pounds (682 kg), $S = 2.13$ for a human habitat, $IOC = 2000$, $B = 8$ for the many previous prototypes and test units, and low difficulty, $D = -2.0$. The total cost is estimated at \$45 million. The cost per delivered kilogram is \$45,000k/682 kg = \$66 k/kg.

For a Mars surface mission, suppose $Q = 1$, $M = 1,500$ pounds (682 kg), $S = 2.46$ for crewed planetary lander, $IOC = 2025$, $B = 10$ for past and future prototypes and units, and the difficulty is average, $D = 0$, considering the higher reliability needed for Mars. The total cost is estimated to be \$1,241 million. The cost per delivered kilogram is \$1,241 million/682 kg = \$1.82 million/kg. This is a much higher cost per kilogram than for the Shuttle or ISS, which are less difficult than planetary missions. A very high cost is expected. "The cost of a human-crewed mission to the Moon or Mars is typically millions of dollars per delivered kg." (Wertz and Larson 1996, p. 254)

3. Inflation adjustments

The AMCM formula estimates costs in millions of 1999 dollars. Past inflation tables can be used to adjust cost to current dollars. Sometimes projected future inflation is used to estimate future costs. (NASA Systems Engineering Handbook 2007, p. 127) The NASA New Start Inflation Index shows an inflation factor of 1.570 from 1999 to 2015 and 2.009 from 1999 to 2025. (NASA New Start Index Inflation Index) Inflation adjustments are necessary in accurately estimating actual costs but might be omitted in trade-off studies if only relative costs are important.

B. The commercial PRICE-H hardware cost model

The PRICE parametric cost models dominate the commercial market and are frequently used in aerospace. PRICE models exist for hardware development, hardware maintenance, software development, life-cycle costs, and scheduling. They are distributed by Parametric Review of Information for Costing and Evaluation (PRICE) Systems Solutions.

The PRICE H Hardware cost model uses industry-specific parametric modeling to estimate costs, resources, and schedules for structural, electro-mechanical and electronic components and complex assemblies. A subscription is required and NASA holds an agency wide license. NASA has annually recalibrated PRICE-H for space missions.

PRICE-H contains hundreds of Cost Estimating Relationships (CERs) based on confidential data from thousands of projects including space hardware. PRICE-H estimates the hardware development and production cost of most manufactured hardware, but it requires extensive detailed inputs. The most fundamental input is mission classification, such as human rated space, since there are different models for different mission types. The most basic input parameters are two masses, the active electronics mass and the less costly mechanical/structural mass. The most important elements of the model are the costs per unit mass for electronics and mechanical/structure.

These are obtained from tables or by calibrating the model using relevant past costs. The cost estimates thus depend directly on the hardware mass.

Users identify hardware items at each level of the work breakdown structure. Price H then aggregates the cost of assemblies into a full system cost. The number of development and production units and the schedule milestones are also required. A production learning curve may be defined.

PRICE H uses three qualitative complexity variables to distinguish hardware having higher or lower cost per unit mass. These parameters are the mechanical, electronic, and engineering complexity. Engineering complexity reflects the scope of the development task, the skills of the development organization, and the amount of design repetition. The complexities may be taken from built-in reference tables or the cost estimator may calibrate the model based on experience, judgment, and even the acceptability of the final cost result. The quantitative masses and the qualitative complexities together largely determine the cost estimates. (Greenberg 1992, pp. 85-86) (Guerra and Shishko 2000, p. 945) (PRICE 2014) (Trivailo et al. 2012)

The PRICE H cost model is usually applied by an experienced cost estimator working closely with engineering, management, and the customer for the estimate. PRICE acknowledges that “You can manipulate the inputs to get any answer you want out of that model.” This is explained as a desirable ability to tailor the model to match the known historical data and thus produce sound cost results. It is further acknowledged that, “The pressure to produce a popular estimate is great. Some estimators bow to that pressure.” (Fad 2013) The knowledge, ability, and professional integrity of the cost estimator will affect the quality of the cost estimate. The cost estimator should not be a member of the project being estimated, and the best arrangement would be an independent and impartial cost estimating organization.

PRICE H seems too large, complicated, indeterminate, and labor intensive to be used to quickly compare the costs of multiple alternate projects. It is much more suitable to provide a deep contextual and evolving understanding of the cost of a large project. PRICE H thus strongly contrasts with the AMCM model, which is quite easy to set up in a spreadsheet and use without specialized cost estimating knowledge. AMCM uses fewer, more objective, and totally quantitative inputs to produce a less adjustable result.

C. The NASA-Air Force Cost Model (NAFCOM)

The NASA-Air Force Cost Model (NAFCOM) parametric cost estimating tool was developed by the Marshall Space Flight Center's (MSFC) and is used for crewed spacecraft, uncrewed spacecraft, and launch vehicles in the early phases of development. It uses multivariable cost estimating relationships (CERs) which are based on historical NASA and Air Force space projects. New missions are added with each release of NAFCOM. There have been twelve releases since 1989 and it now includes over 155 NASA and Air Force space flight hardware projects.

Early in a project, NAFCOM can produce weight based estimates using only a Work Breakdown Structure (WBS) and mass estimates. NAFCOM's multivariable cost estimating allows the estimator to select appropriate historical data-points from the database. Quantitative inputs include weight, materials, power requirements and design life. Technical and programmatic complexity factors are applied to the CERs. They consider contractor experience, management layers, technology readiness, and requirements changes.

The model produces costs for DDT&E and for recurring production costs at the subsystem or component levels. There are cost models for structure, thermal, attitude control, power, environmental control and life support, crew accommodations, propulsion, command and data handling. NAFCOM includes elements in the Environmental Control and Life Support (ECLS) subsystem. The costs for system integration, test, ground support, systems engineering, and program management are estimated separately and added. The Space Operations Cost Model (SOCM) is integrated into NAFCOM. (Guerra and Shishko 2000, pp. 945, 7) (NAFCOM 2014) (NAFCOM FAQ) (Trivailo et al. 2012)

The NAFCOM software is available on request. NAFCOM is a Windows desktop application. Microsoft Excel is also required. The government version is restricted and a contractor releasable version has the historical weights and costs hidden. All CERs and model inputs are the same between versions. (NAFCOM 2014) (NAFCOM FAQ)

NAFCOM is being replaced by a new model called Project Cost Estimating Capability (PCEC) with similar capabilities. Limited technical support is being provided to current NAFCOM12 users. (Prince et al. 2014) NAFCOM, like PRICE H, should be used by an experienced cost estimator.

D. Spacecraft/Vehicle Level Cost Model (SVLCM)

The Spacecraft/Vehicle Level Cost Model (SVLCM) is a top level model which provides instant rough-order-of-magnitude estimates for spacecraft development and production costs. SVLCM is a highly simplified version of NAFCOM and is available on-line. The user inputs are the project name, project type, the system dry weight in pounds or kilograms, the quantity of units, and a learning curve for multiple units. The project types modeled are

liquid rocket engines, manned spacecraft, unmanned planetary spacecraft, launch vehicles, unmanned Earth orbiting spacecraft, and scientific instruments. The manned spacecraft costs are based on eight data points. Life support cost models are not specifically included. Like NAFCOM, SVLCM produces the costs for development and production in millions of FY1999 dollars. (Global Security 2014) (Trivalo et al. 2012)

1. SVLCM cost estimates

Table 2 shows the SVLCM cost estimates for two different manned spacecraft systems with masses of 100 and 1,500 pounds. The equivalent AMCM cost estimates are shown for comparison.

Table 2. SVLCM cost estimates for manned spacecraft systems with masses of 100 and 1,500 pounds.

Parameter	Values	
Project type	Manned spacecraft	Manned spacecraft
System dry weight in pounds	100	1,500
Quantity of units	1	1
Learning curve	85%	85%
Development cost, M\$	147	653
Production cost, M\$	7	43
SVLCM total cost, M\$	154	696
Comparable AMCM total cost, M\$	15 - 195	45 - 1,241

The SVLCM estimated costs are 154 million for a 100 pound unit and 696 million dollars for a 1,500 pound unit. Both AMCM and SVLCM costs are in 1999 dollars. (Global Security 2014) The comparable AMCM total cost is the range of total cost estimates for a system having the same weight. The SVLCM estimated costs are in the upper middle range of the AMCM estimated costs, at 79 percent and 56 percent of the AMCM maximums. The AMCM model is more adaptable and useful than the SVLCM model.

E. Project Cost Estimating Capability (PCEC)

The Project Cost Estimating Capability (PCEC) has been developed as the replacement for NAFCOM. NAFCOM was failure prone, suffered from performance issues, and required excessive support. The NAFCOM software architecture reflected a WBS that differed from the NASA Standard WBS. It provided insufficient insight into the functioning of the model and the development of the CERs. (Prince et al. 2014)

NASA has developed PCEC to solve these problems and also to address diverse cost estimating requirements and to emphasize problem driven analysis over tool driven analysis. PCEC is an Excel based system with a user interface and WBS and CER libraries. The core methods and capabilities of NAFCOM, such as first pound cost and multivariable CER equations, are implemented in PCEC. COTS tools now provide some functions previously contained in NAFCOM. The objective is capability and flexibility rather than ease of use. PCEC was initially distributed only to NASA but will be made freely available as was NAFCOM. (PCEC 2014) (Prince et al. 2014)

F. DDT&E cost estimation summary

The AMCM is simple and quick to use. It does not require specialized software or a trained operator. It seems the best cost estimator for use during system trade-offs and initial technology assessment. Repeatable, defensible relative costs comparisons would be more important than a refined but subjective best guess cost estimate. The Price-H cost model and the PCEC that is replacing NAFCOM are suitable for the careful estimation of the cost of a large development project. We next consider launch and emplacement cost.

III. Launch and Emplacement (L&E) cost estimation

Some missions such as ISS operate in Low Earth Orbit (LEO). Missions beyond LEO will typically reach LEO first and later depart to the moon, an asteroid, or Mars. The cost to launch and emplace space systems thus has two components, the cost of launch to LEO and the additional cost for emplacement at the mission location beyond LEO.

A. Cost of launch to Low Earth Orbit (LEO)

The Space Shuttle cost to launch to Low Earth Orbit (LEO) was typically quoted as \$20 k/kg. The usual cost for launch to LEO has been about \$10 k/kg for many decades, but this high cost has been considered a major impediment to space exploration and development. (Wertz and Larson 1996, p. 125)

A yearly Space Shuttle budget of 4 billion dollars for 10 planned launches of 16,000 kg to LEO corresponds to a cost of \$25 k/kg. Since there were 135 shuttle flights over 30 years, the flight rate was only 4.5 launches per year, which corresponds to a higher cost of \$55 k/kg. This launch and operations cost does not include development cost, which could add another half a billion dollars per launch. (Strickland 2013) Adding development cost, the cost of launch to LEO could have been as high as \$87 k/kg.

NASA is developing the Space Launch System (SLS). Its initial capability will be 70,000 kg to LEO and one quoted cost is 500 million dollars per launch. (Wikipedia, Space Launch System 2014) This corresponds to a reasonable cost of \$7.140 k/kg. However the 500 million dollar cost per launch is an unofficial NASA target that seems to reflect only the incremental cost per launch, without the initial development and continuing operations costs. (Strickland 2013) About 8 billion dollars will be required for SLS development through the first flight in 2017 or 2018. (Aitoro 2014) SLS has been criticized because its mission is undefined and few launches are definitely planned, but NASA hopes for once-a-year launches after the first crewed Orion flight in 2021. (Davis 2014) If there were a total of 16 launches, allocating the 8 billion dollar development cost would add a second 500 million dollar cost to each launch and the cost per kilogram would double to \$14,280 k/kg.

Future NASA and commercial launch vehicle development could greatly reduce the cost per kilogram to reach LEO. "Today, it costs \$10,000 to put a pound of payload in Earth orbit. NASA's goal is to reduce the cost of getting to space ... developing technologies that target a 100-fold reduction in the cost of getting to space by 2025, lowering the price tag to \$100 per pound." (NASA ASTP 2000) Space X's long planned Falcon Heavy has its first launch projected for 2016. It is expected to launch 53,000 kg to LEO at a cost of 85 million dollars, a cost of only \$1.6 k/kg. (Space X, Falcon Heavy) Falcon Heavy cost estimates per launch have been higher, up to 135 million dollars, giving a higher cost of \$2.5 k/kg to LEO. (Wikipedia, Falcon Heavy)

A reasonable historically based cost for launch to LEO is \$10 k/kg. An optimistic estimate for the future would be \$2.5 k/kg, a 75% reduction. The likely worst case might be \$25 k/kg, ten times the best case.

B. Computing mass ratios for emplacement beyond LEO

A moon or Mars mission requires launching to LEO both the payload and the propulsion system - the rocket and propellant - needed to get the payload to its final destination. The surface payload must be placed on the moon or Mars. The transit vehicle must be placed in moon or Mars orbit and later returned to LEO. The emplacement cost depends on the ratio of the total initial LEO mass to the final payload mass. The initial mass includes the propellant but the final mass does not. These initial/final mass ratios depend on the required Δv and the specific impulse of the propellant. Typical initial/final mass ratios from LEO to the moon or Mars and landing or return are shown in Table 3 below. (Condon et al. 2000, pp. 276-279)

Table 3. Initial/final mass ratios beyond LEO.

Moon	
LEO to moon orbit and landing	6.7
LEO to moon orbit and return to Earth	5.0
Mars	
LEO to Mars orbit and landing	4.8
LEO to Mars orbit and return to Earth	13.2

The Moon landing requires rocket powered lunar orbit insertion and descent. The Mars landing saves propellant mass by using aerobraking for Mars orbit insertion followed by combined parachute and powered descent. The initial/final mass ratios indicate the need to launch to LEO propellant that is 4.8 to 13.2 times as massive as the payload plus the transit and landing rockets. The rocket mass is typically 15% of the propellant mass. (Petro 2000, p. 405) (Wertz and Larson 1996, p. 142) Table 3 gives the ratio of payload plus rocket plus propellant mass to the payload plus rocket mass, so the ratio of payload plus rocket plus propellant mass to the payload mass alone will be substantially higher. The exact stack-to-payload mass ratios can be calculated for any particular mission plan. Missions that use only chemical propulsion will have significantly higher mass ratios, but these can be reduced by using aerobraking and gravity assist. (Jones 2003-01-2635) (Jones 2012-3618)

C. Location factors or gear ratios for locations beyond LEO

The stack-to-payload mass ratios are often called location factors or gear ratios. The location factor is the ratio of the total payload, rocket, and propulsion mass necessary in LEO to emplace the payload mass at its mission destination. The total mass required in LEO is simply the payload mass multiplied by the location factor or gear ratio. (Fisher et al. 2003) (BVAD 2004)

Table 4. Location factors or gear ratios for locations beyond LEO.

	(BVAD 2004)	(BVAD 2008)	Average
Moon			
LEO to moon orbit and landing	6.98	7.2	7.1
LEO to moon orbit and return to Earth	7.36	9.1	8.2
Mars			
LEO to Mars orbit and landing	3.77	2.77	3.3
LEO to Mars orbit and return to Earth	6.77	5.77	6.3

The nominal location factors from the Life Support Baseline Values and Assumptions Document (BVAD) are given in Table 4. The (BVAD 2004) and (BVAD 2008) values differ somewhat. The (BVAD 2008) (BVAD 2010) and (BVAD 2014) location factors values are identical. The BVAD location factors for Mars are based on the Mars Dual Lander architecture which uses aerobraking. The BVAD 2004 estimates for the moon are based on a similar architecture, while BVAD 2008 and later estimates for the moon are based on the L1 Gateway architecture.

Connolly's Mars design example in *Human Spaceflight* uses solar electric propulsion to ferry cargo slowly from LEO to High Earth Orbit where the Mars habitat/lander is assembled. Nuclear propulsion in LEO was ruled out. A chemical rocket is used for a fast 180 day crew transit to Mars. The stack-to-payload mass ratio is 3.1 for the habitat/lander, and is similar to the BVAD values (Connolly 2000, pp. 986-987, 998-999) (Jones 2012-3618)

IV. Operations cost estimation

The operations phase of a human space mission begins after launch and continues until the crew returns to Earth. The operations cost includes crew training, ground support, mission control and planning, and data analysis. Ground support provides constant coverage with on-call expertise for maintenance and trouble-shooting. Sustaining engineering is needed to support maintenance and trouble-shooting. The system complexity and the mission duration are the two major drivers of operations cost. (Wertz and Larson 1999, pp. 214-218) (Jones 2003-01-2635)

Space operations costs can be approximately predicted as an additional percentage of the system development cost every year. Mission constraints and systems design choices tend to drive DDT&E and operations costs in the same direction. Complex human missions, severe environments, and higher risk aversion increase both DDT&E and operations cost. New technology, large amounts of software, complex monitoring and control, tight margins, and multiple operational modes do also. (Wertz and Larson 1996, pp. 214-218) (Jones 2003-01-2635)

Human space programs before the space shuttle were relatively short term and had small operations costs. The space shuttle's estimated total cost for the first ten years had 58% for operations and 37% for DDT&E, so the operations cost for ten years is 157% of the DDT&E cost. Shuttle operations therefore cost roughly 15.7% of DDT&E per year, but this includes launch, which is usually estimated separately. The early estimated total cost of the ISS including ten years of operations had 51% for operations and 45% for DDT&E. The ten year operations cost is 113% of the DDT&E cost. ISS operations cost is roughly 11% of DDT&E per year, not including launch. (Guerra and Shishko 2000, p. 938) (Jones 2003-01-2635)

The Johnson Space Center (JSC) developed the Mission Operations Cost Model (MOCM). It is a high-level estimating tool that provides a quick rough order of magnitude cost estimate for spacecraft mission operations. The MOCM estimates the average annual operations costs for manned, unmanned, or planetary missions based on the total development and production cost of the spacecraft. The JSC MOCOM was maintained as an online calculator but is no longer available. (NASA CEH) The MOCM estimated manned spacecraft operations cost as equal to 10.9% of the total development and production cost per year. (Jones 2003-01-2635)

V. Life Cycle Cost (LCC)

The Life Cycle Cost (LCC) of a space mission is the sum of the costs for Design, Development, Test, and Evaluation (DDT&E), Launch and Emplacement (L&E), and Operations. The LCC of a hardware system is estimated for four different missions, a future space station, a moon base, a Mars transit vehicle, and a Mars base. The mission parameters and costs are shown in Table 5

Table 5. Mission Life Cycle Cost (LCC).

		Mission			
AMCM Parameters		Space station	Mars transit	Moon base	Mars base
Q	Quantity	1			
M	Mass, lb	1,500			
M	Mass, kg	682			
S	Specification	2.13	2.13	2.46	2.46
IOC	Initial date	2030			
B	Block	2			
D	Difficulty	-2	0	-2	0
DDT&E cost					
	DDT&E cost, \$M	98	242	419	1,032
	DDT&E cost per kg, \$k	144	355	614	1,513
	DDT&E cost % of total	46%	78%	45%	84%
L&E cost					
	Cost to LEO, \$k/kg	10			
	Gear ratio	1	6.3	7.1	3.3
	L&E cost, \$M	7	43	48	23
	L&E cost per kg, \$k	10	63	71	33
	L&E cost % of total	3%	14%	5%	2%
Operations cost					
	Mission duration, years	10	1	10	1.5
	Operations cost per year/DDT&E	0.11			
	Operations cost, \$M	108	27	461	170
	Operations cost per kg, \$k	159	39	676	250
	Operations cost % of total	51%	9%	50%	14%
Total cost					
	Total cost, \$M	214	312	928	1,224
	Total cost per kg, \$k	313	457	1,361	1,795

The system costs are high, 100's of millions of dollars, and they increase as the missions go outward from a space station to a moon base, a Mars transit vehicle, and a Mars base. The LCC per kilogram increases from about \$300k to \$2M per kilogram. The costs are in 1999 dollars and are more that fifty percent higher now and would be more than double in current dollars by the end of the next decade.

Most of the parameters are the same for all missions. The identical parameters are the quantity, mass, initial operating date, block, cost to launch to LEO, and operations cost per year as a fraction of DDT&E cost. The AMCM specification, S, is 2.13 for a manned habitat and 2.46 for a planetary lander. The difficulty was set to -2, easy, for a future space station and moon base since quick resupply or crew return are possible. The difficulty was set to 0, average, for the Mars transit vehicle and Mars base because of their much more difficult reliability requirement. The relative costs of DDT&E, L&E, and operations are shown in Figure 1.

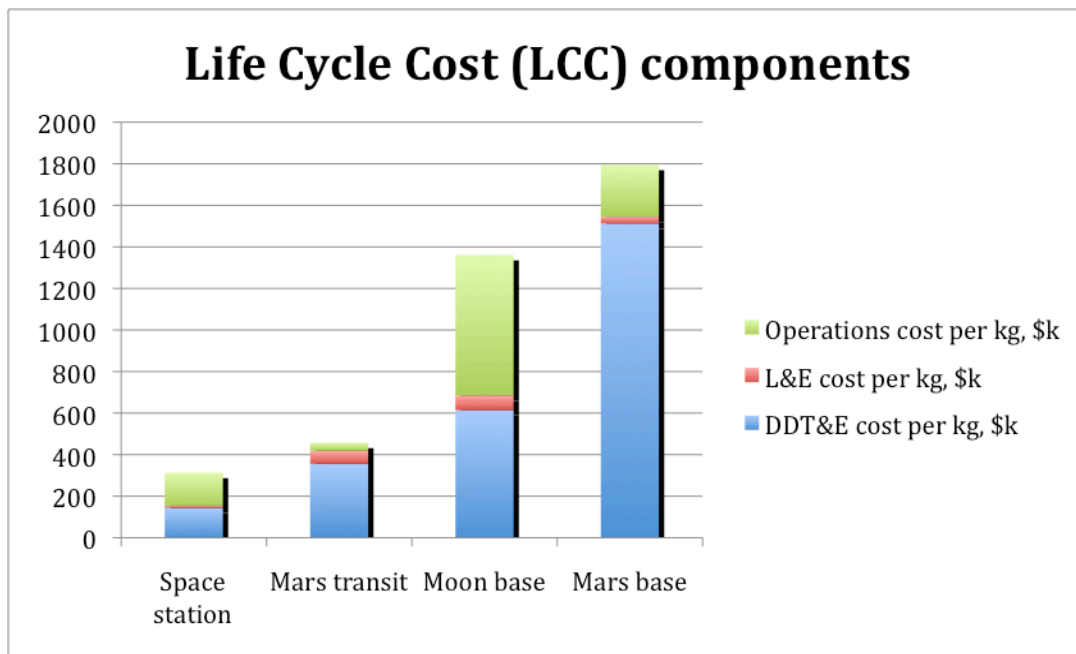


Figure 1. Costs of DDT&E, L&E, and operations in \$/kg.

The DDT&E cost is always a major portion of the mission cost, about 45% for a space station or Moon base and about 80% for Mars transit and a Mars base. The DDT&E cost is a smaller part of the total for a space station or Moon base because these are ten year long missions with high operations costs,

The L&E cost is relatively small, averaging about 6%. The anticipated reduction of LEO launch cost by a factor of four, to \$2.5 k/kg, would reduce total LCC by only 4 or 5%. An increase by a factor of four would increase average mission cost only by 18%.

The operations costs are very high for the two ten year missions, about 50% of the total for space station and moon base. The high operations costs reflect high DDT&E cost and long mission duration.

The facts that the L&E cost is negligible and that the operations cost is directly proportional to the DDT&E cost makes it clear that the DDT&E cost is the major driver in LCC. The AMCM formula suggests that DDT&E cost might be reduced by reducing the system mass and functionality, by using designs with a long multigenerational heritage, and by reducing the programmatic and technical difficulty. It is thought that the culture of human space development must change to reduce cost. Some suggestions are concurrent engineering, integrated design environments, simulation based design, and use of commercial parts, practices, and organizations. (Guerra and Shishko 2000, pp. 954-7)

The general approach cost estimating shown in Table 5 seems reasonable and useful. The LCC computation presented can easily be revised for different assumptions and missions. It is too simple to capture second order effects. For instance, spending more on DDT&E to achieve lower mass would tend to incorrectly reduce the estimate of DDT&E cost. Similarly, spending more on DDT&E to decrease operational problems would wrongly tend to increase the estimate of operations cost. The AMCM estimate of DDT&E cost produces only a rough historically based estimate that can be useful but is necessarily inexact.

VI. Conclusion

A quick rough order of magnitude estimate of space systems' Life Cycle Cost (LCC) can be provided by adding estimates of the costs for Design, Development, Test, and Evaluation (DDT&E), Launch and Emplacement (L&E), and operations. The DDT&E cost estimate is developed using the Advanced Missions Cost Model (AMCM). The L&E cost estimate is based on the historic cost of launch to Low Earth Orbit (LEO) and the mission-specific stack-to-payload mass ratio. The operations cost estimate is a historically based additional percentage of the DDT&E cost per year.

A rough LCC estimate can be used in preliminary technology selection and architecture trade-offs and to compare alternate mission scenarios. The model presented here could be updated or tailored for specific technology areas. More detailed and flexible models should be used in project planning and management.

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