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Spacecraft Design to a Cost Target

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Abstract

Perfect performance of every system is critical for space missions. Identifying capable designs is a challenging process, and one that often comes at the expense of exceeding cost targets. The Cost As an Independent Variable (CAIV) approach helps mitigate this issue by treating cost as a primary consideration in the design or procurement of systems. Establishing a fixed cost target sets a ceiling for the cost versus performance trade-off and, in the case of NASA's in-house spacecraft, enables more cost-conscious decision making. This paper examines application of CAIV to identify upper bounds for parameters (mass, power, quantity, etc.) early in the process of designing a spacecraft that satisfies mission requirements. It describes the process of developing, maintaining, and explaining the limitations of this capability, and addresses potential applications of the approach to other commodities.

Keywords: Cost Management, Data-Driven, Early Cost, Parametrics, Space

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Introduction

1.1 History of Spacecraft Design

On October 4, 1957, the Soviet Union launched Sputnik 1, a 58-centimeter sphere of aluminum weighing 83 kilograms, which carried a small radio beacon emitting regular beeps to communicate its location. Sputnik 2, larger at 508 kilograms, followed only weeks later, and the United States successfully launched Explorer 1 within months (Launius, 2005). Since this time, space missions have become more ambitious, while the required hardware has become increasingly complex. Today, the James Webb Space Telescope must travel nearly 1.5 million kilometers to Lagrange Point 2 and deploy a tennis court-sized sunshield to protect its 6.5-meter mirror, while the Parker Space Probe needs to withstand temperatures as high as 1377 degrees Celsius as it encircles the Sun (NASA SMD, 2024; NASA SMD, 2023).

The National Aeronautics and Space Administration (NASA) is responsible for deploying a large portion of space-bound hardware, particularly those facilitating an increased understanding of Earth Science, Astrophysics, Heliophysics, and Planetary Science. A NASA mission can be best understood via a Work Breakdown Structure (WBS), which organizes each of its elements. The standard WBS for NASA projects is shown in Figure 1.

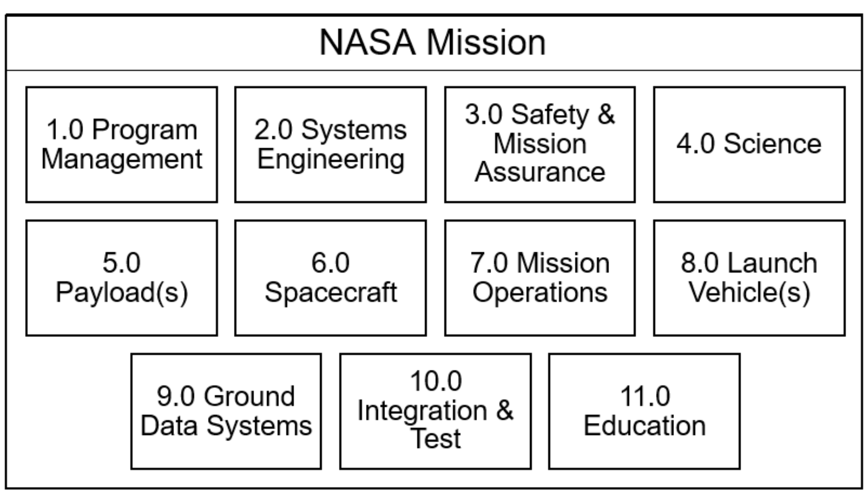


Figure 1: NASA WBS (NASA STI, 2018)

Several key terms in this WBS are critical to understand:

- Mission: A comprehensive endeavor in space with specific scientific objectives, requirements, timelines, and centralized leadership. This is also referred to as a Project.
- Payload: The equipment used to perform scientific experiments, technology demonstrations, or advanced communications and the associated data-gathering functions.
- Spacecraft: The platform for carrying payload(s) and other essential equipment in space.
- Launch Vehicle: The system used to launch a spacecraft into its operational environment or on a trajectory towards its target location.

Each mission relies on several distinct subsystems, all of which must flawlessly execute specific functions. For example, a spacecraft generally needs a Command and Data Handling (C&DH) subsystem to store information and send commands; a Communications subsystem for data transfer to and from data centers; a Guidance, Navigation and Control (GN&C) subsystem to identify position in space and reorient towards an intended destination; as well as Mechanical, Power, Propulsion, and Thermal Control subsystems and occasionally others. The technology leveraged in each subsystem has continuously evolved, with new innovations arising, being tested, and quickly becoming standard. This constant advancement has enabled humanity to achieve objectives that would have seemed impossible decades ago, but it has also kept the cost of spacecraft high.

Meanwhile, funding for space missions remains limited. Over the past two decades, NASA’s budget has experienced an annual increase of approximately 0.2%, adjusted for inflation (The Planetary Society, 2023). The small magnitude of this increase is noticeable when considering the agency’s funding as a portion the total federal budget. A comparison is shown in Figure 2.

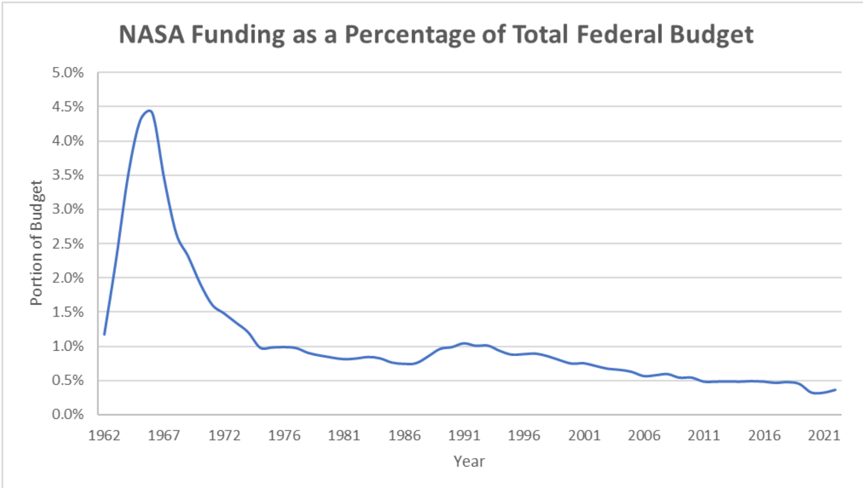


Figure 2: NASA Funding as a Percentage of Federal Budget (OMB, 2023)

Mission budgets are as tights as ever and spacecraft development is a major cost driver. Yet, due to a lack of available methods and tools, few engineers have started to incorporate cost as a variable during the early stages of the design process. Instead, the initial effort focuses on identifying a functional point design, which then goes through cycles of costing and redesign until an affordable configuration of hardware is established. The flow of work is depicted in Figure 3.

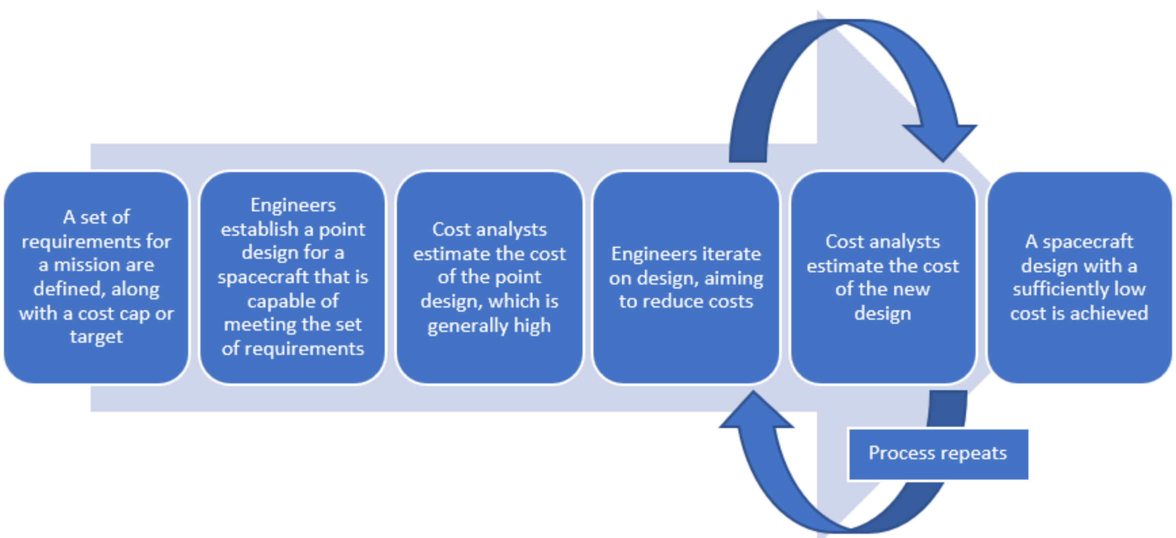


Figure 3: Traditional Process Flow for Spacecraft Design

This traditional method has mixed results in meeting cost constraints. It works well when a planned spacecraft resembles a recently flown system. However, when the spacecraft uses a unique combination of hardware, this process can be cumbersome and require multiple iterations over an extended period. Even worse, the initial design may be deemed so unaffordable that it is easier to scratch it entirely than to revise it. This restarts the entire process. While an engineering team would proceed into a new cycle with a better understanding of system configurations and financial challenges, this additional work would require the commitment of more time and money.

An improvement to this workflow includes adopting a Design to Cost (DTC) approach. Here, leadership builds financial considerations into the design process by setting a target cost, which is used to establish an upper limit on a technical parameter (e.g., mass, power, or quantity) for the spacecraft before the process formally begins. With this modification, the new flow can be seen in Figure 4.

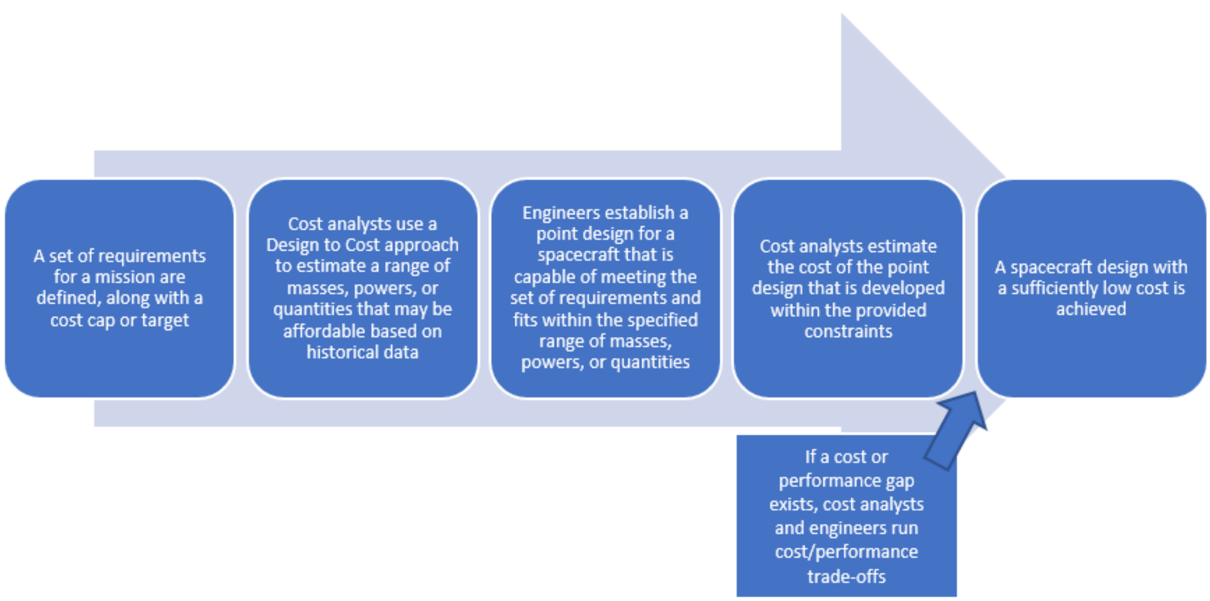


Figure 4: Process Flow with Design to Cost

1.2 Principles and Applicability of CAIV

DTC is one of several techniques that can be performed using parametric relationships with Cost As an Independent Variable (CAIV). CAIV treats operational requirements and cost objectives as equal, thereby turning cost into a constraint that influences decisions rather than an outcome of decisions made for other reasons (e.g., technical, political, etc.). The CAIV approach is most effective when applied early in development as consequential choices are made that impact a program throughout its duration (ICEAA, 2019). Leveraging CAIV at this stage can reduce the need to make drastic changes to rapidly reduce costs once a program has a more mature design.

One of the key tenets of CAIV is running trade-offs. These trade-offs take two primary forms:

- Cost/Requirement Trade-off: A decision made by government to relax requirements to reduce costs, or to tighten requirements at the expense of higher cost.
- Cost/Performance Trade-off: A decision made by managers, engineers, or others involved in executing a task to decrease the performance of a system (within acceptable limits) in order to reduce costs, or to increase performance at the expense of higher cost.

When conducting these trades, Cost Analysts typically consider the Life Cycle Cost or Total Ownership Cost, both of which consider the full expense of building, deploying, and maintaining a system. The trade space is generally bounded by an Objective Cost serving as the best-case scenario and a Threshold Cost representing the worst-case scenario. Performance, meanwhile, is measured using various metrics (e.g., speed, reliability) that differ based on the program and are bound by Objective Performance and Threshold Performance (NASA CAD, 2008). A line representing the Set of Optimal Solutions runs through the middle of the plane on which trades are conducted. At any point along this line, an increase in performance requires an even greater increase in cost, and a decrease in cost requires an even greater decrease in performance. The plane is made more crowded by uncertainty in the relationship between these factors, so a risk reserve must be created early on. As a system is developed, the size of this reserve can gradually decrease, but it should not fully disappear at any point (Kaye et al., 2000). A depiction of the trade space is shown in Figure 5.

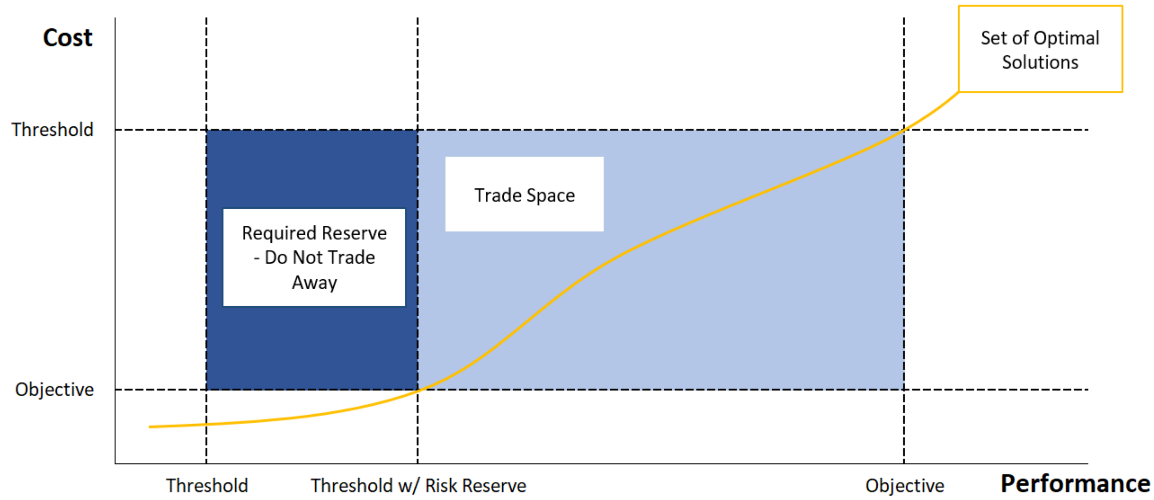


Figure 5: Cost-Performance Trade Space

CAIV has been employed by a number of programs since the late 1990s with varying levels of success. Among the CAIV Flagship Programs identified in a 1996 presentation by the Institute for Defense Analyses are: Evolved Expendable Launch Vehicle (EELV), Multifunctional Information Distribution System (MIDS), Joint Air-to-Surface Standoff Missile (JASSM) and Air Intercept Missile (AIM)-9X (Rush, 1997). These efforts focused on a range of different commodities. Spacecraft, however, are absent from the list.

Regardless, CAIV is particularly useful when designing spacecraft, as these systems are built to be adaptable. Depending on what a mission requires, they can be different sizes, generate various amounts of power, and be simple or complex. These parameters can all be tweaked. By establishing a relationship between cost and one of these variables (e.g. size), it is possible to estimate a range of values for that parameter that are likely to be affordable. The spread can be used to set constraints on the design process. There are significant advantages to using this technique. The Cost Estimating, Modeling, and Analysis (CEMA) Office at Goddard Space Flight Center (GSFC) is experiencing these advantages, having developed a Spacecraft Mass Estimation Capability (SMEC) to support engineering teams.

The Spacecraft Mass Estimation Capability (SMEC)

2.1 Concept and Development Approach

The CEMA Office created SMEC, an Excel spreadsheet tool, to aid the process of designing spacecraft to a cost target. SMEC leverages a dataset of historical NASA missions as the basis for analogy and parametric methodologies, which are used to estimate a range of masses for spacecraft that may be affordable after incorporating uncertainty. Mass was selected as the performance parameter to estimate due to the feasibility of constraining it and its high correlation to cost in space hardware. Engineers commonly limit mass to ensure a system can fit within a particular launch vehicle, so restricting masses does not introduce a new constraint but rather adjusts an existing one. While mass may not be a traditional performance parameter for most hardware, bigger is often better when it comes to spacecraft. Larger (and therefore more massive) spacecraft can transport more scientific instruments, and hold larger solar panels, along with more robust equipment for the distribution and storage of electrical power. These factors made mass a clear choice as a variable to use opposite cost.

The process of developing SMEC included four steps, which were:

1. Collect and normalize cost and technical data to obtain the inputs and outputs that drive the methodology.
2. Develop methods to obtain a Spacecraft Cost Target from a Mission Cost Target, using analogy, and to estimate a range of values for Spacecraft Mass based on the Spacecraft Cost Target, using parametric relationships with CAIV.
3. Validate the CAIV equations using visual checks and goodness-of-fit statistics.
4. Design an interface for the capability.

2.2 Data Collection and Normalization

Various data sources contain detailed cost and technical information on NASA missions, including the spacecraft flown on these missions. One such repository is the One NASA Cost Estimating (ONCE) database, developed by NASA Headquarters and accessible to NASA civil servants and contractors. ONCE houses technical reports and presentations in addition to standardized cost data. The Cost Analysis Data Requirement

(CADRe) is most useful source of cost data in ONCE, as it includes three volumes outlining cost, schedule, and technical aspects of a program at each milestone. Aside from ONCE, the Marshall Space Flight Center (MSFC) maintains the Resource Data Storage and Retrieval Analysis Center (REDSTAR), another valuable data repository. SMEC leveraged a comprehensive dataset composed of ONCE and REDSTAR data that MSFC normalized for the for the purpose of creating NASA's Project Cost Estimating Capability (PCEC), a model used to estimate the costs of spacecraft and other elements of a space mission (NASA MSFC, 2023).

The data normalization effort for SMEC aimed to ensure that missions could be categorized into distinct groups for the analogy and parametric estimating methodologies. For this reason, the more than 100 variables in PCEC dataset were trimmed to the more manageable subset in Figure 6.

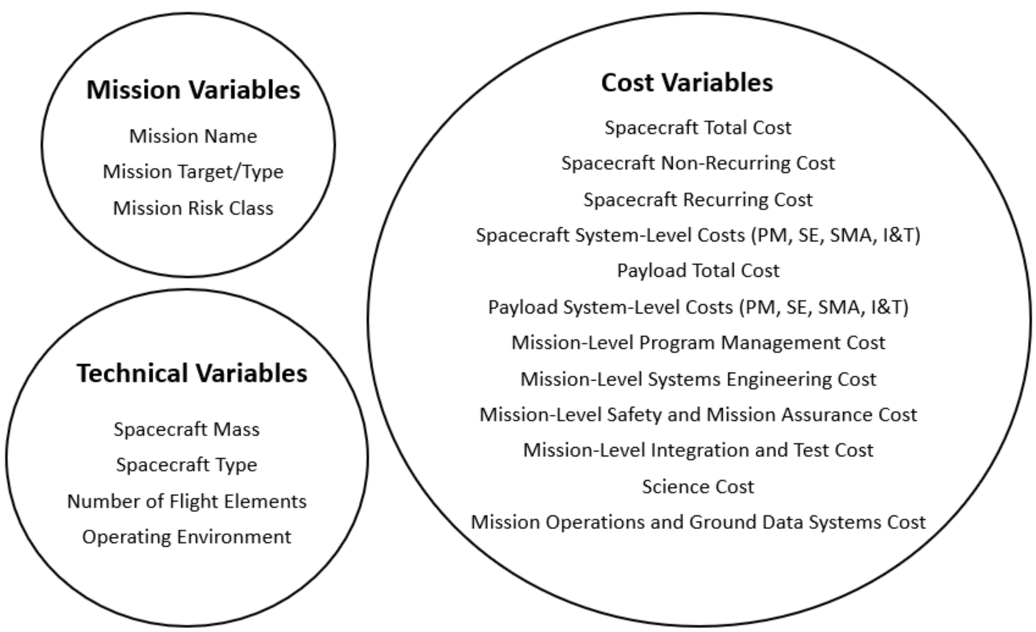


Figure 6: Subset of Variables for SMEC

Several of these variables were transformed from their initial categorization structure to a new one. For example, the Mission Target/Type variable and the Operating Environment variable each had several options and were similar enough to combine into a single variable called Destination. This new, simplified variable had only two choices: Earth Orbiting or Deep Space.

Certain observations were excluded, including those with unusually low or missing values or those lacking costs at a sufficiently detailed level. In total, 42 and 63 observations were used for the analogy and parametric techniques, respectively.

2.3 Method Development

2.3.1 Analogy Method for Allocation of Funds to Spacecraft

A Spacecraft Cost Target, a required input for the SMEC CAIV regressions, cannot always be provided by an engineering team. Frequently, the spacecraft design process begins early, when the funds available for each mission element are unknown. At this point, the only known cost to aim for is a Mission Cost Target outlined in a government solicitation (e.g., a NASA Announcement of Opportunity (AO)). To overcome this issue, a methodology was devised to estimate a Spacecraft Cost Target based on the Mission Cost Target and the additional inputs listed in Table 1.

Table 1: Inputs for Allocation of Funds Step

Category	Data Field	Description	Options
Cost Data	Fiscal Year $	The common year for all cost inputs and outputs, used for escalation or de-escalation.	Year (No Restrictions)
	Pass-Through: Phase A	The cost incurred during Phase A, which is defined as the time used to develop the mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	$K (No Restrictions)
	Pass-Through: Payload (WBS 5, Phase B-D)	The cost incurred developing and producing the payload (generally scientific instruments) throughout Phases B-D, including relevant overhead.	$K (No Restrictions)
	Pass-Through: Launch Vehicle (WBS 8, Phase B-D)	The cost incurred developing or procuring a launch vehicle throughout Phases B-D, including relevant overhead.	$K (No Restrictions)
	Pass-Through: Phase E	The cost incurred during Phase E, which is defined as the time from end of on-orbit checkout to the end of the primary science mission.	$K (No Restrictions)
	Pass-Through: Phase F	The cost incurred during Phase F, which is defined as the time used to implement the systems disposal plan and perform analyses of the returned data.	$K (No Restrictions)

Category	Data Field	Description	Options
Mission Parameters	Mission Risk Class	The risk class assigned to the mission per the NASA Space Flight Program and Project Management Requirements.	Class A Class B Class C/D
	Destination	The general location of the of solar system body that the spacecraft will visit or orbit in its Primary Mission.	Earth Orbiting Deep Space
	# of Identical Spacecraft	The number of identical spacecraft to be produced and flown.	# (No Restrictions)
Method Settings	Percent Non-Recurring Engineering	The percentage of cost for the first spacecraft unit that is not incurred on subsequent units.	39% - 46%
	WBS Allocation Value	The method used to allocate funds by WBS element.	Mean Median

First, the Mission Cost Target is reduced by the amounts specified in the Pass-Throughs for Phase A, Payload (WBS 5.0, Phase B-D), Launch Vehicle (WBS 8.0, Phase B-D), Phase E, and Phase F. Next, funds are allocated to the remaining elements based on allocations from historical missions. This step is implemented using an analogy method, which works as follows:

1. The tool identifies all missions from its dataset that match the input values for Mission Risk Class and Destination.
2. For this subset of missions, the tool calculates the percentage of the cost in Phase B-D, excluding WBS 5.0 and WBS 8.0, that is allocated to each other WBS element or group of elements.
3. For each WBS element, the tool takes either the Mean or Median allocated percentage value from the subset of missions, based on the selection for the WBS Allocation Value.
4. The tool scales these estimated values to ensure a total allocation equal to 100%. This has no impact if funds are distributed based on the Mean allocations from historical mission, but it is critical if the Median values are used. Consider a theoretical dataset that only includes only three missions. Here, it may be the case that the median allocation to WBS 1.0, 2.0, and 3.0 comes from Mission 3, the median for WBS 4.0 comes from Mission 1, the median for WBS 6.0 comes from

Mission 2, etc. These median values usually sum up to a total that is less than or greater than 100%. Therefore, scaling is required to achieve Adjusted Medians, as illustrated in Figure 7.

Mission	Included (Y/N)	%WBS1,2,3	%WBS4	%WBS6	%WBS7,9	%WBS10
Mission 1	1	16.19%	2.97%	66.24%	10.26%	4.35%
Mission 2	1	11.71%	0.92%	67.16%	15.17%	5.03%
Mission 3	1	15.89%	6.09%	71.17%	5.76%	1.09%
	Mean	14.60%	3.32%	68.19%	10.40%	3.49%
	Median	15.89%	2.97%	67.16%	10.26%	4.35%
	Median (Adjusted)	15.79%	2.95%	66.74%	10.19%	4.32%

Figure 7: Mission Target Cost Allocation by WBS (Example)

The primary value estimated through this process is the total funding allocated to the spacecraft, WBS 6.0. This is referred to as the Total Spacecraft Cost Target. If multiple spacecraft are required for the mission, then this value is subdivided based on an Assumed Percent Non-Recurring Engineering (NRE) selected from a suggested range. Implementing this calculation yields a Spacecraft Cost Target for the first unit of the system.

2.3.2 Parametric Method for Mass Estimation

The CAIV approach is applied using a Mass Estimating Relationship (MER), a regression equation that estimates the mass of a system based on one or more input parameters. While these variables are inherently correlated, the relationship does not need to be causal. For example, consider an MER used to predict mass for a given cost. If A is a constant leading coefficient and B is the exponent to which cost is raised, the general formula would be:

$$Mass = A * Cost^{B}$$

SMEC's implementation of an MER requires the Spacecraft Cost Target and the additional inputs listed in Table 2.

Table 2: Inputs for the MER

Category	Data Field	Description	Options
Cost Data	Fiscal Year $	The common year for all cost inputs and outputs, used for escalation or de-escalation.	Year (No Restrictions)
Mission Parameters	Destination	The general location of the of solar system body that the spacecraft will visit or orbit in its Primary Mission.	Earth Orbiting Deep Space
	Spacecraft Type	The type of spacecraft being operated.	Flyby/Orbiter Impactor EDL Rover
Method Settings	MER Includes Coefficient	Whether the logarithmic MER to be used includes a coefficient, giving it the formula $y = ax^b$, rather than $y = x^b$.	Yes
	MER Uncertainty Distribution	The distribution of uncertainty around the mean value calculated by the MER.	t-Dist.

This step is implemented parametrically as follows:

1. The tool determines whether the mission is Earth Orbiting or Deep Space and the type of spacecraft, based on the input values for Destination and Spacecraft Type, and chooses an MER accordingly.
2. The MER computes a Point Estimate (PE) for Spacecraft Mass using a given Spacecraft Cost Target.
3. Based on the selected MER Uncertainty Distribution, a range of potential mass values is generated around the PE to account for uncertainty.
4. The PE is considered a Maximum Estimated Value (MEV), so an assumed margin is subtracted to obtain a target that represents the Current Best Estimate (CBE). This is necessary because the tool’s dataset contains final measured masses, and it is typical for spacecraft masses to grow from initial estimates. Currently, SMEC assumes a mass growth margin of 30%, which is equivalent to the Mass Growth Allowance plus Mass Margin recommended by the American Institute of Aeronautics and Astronautics (AIAA) for a program at the Authority to Proceed (ATP) milestone (AIAA, 2015).

2.4 Validation of the CAIV Methodology

The MERs at the center of SMEC were selected based on visual checks and goodness-of-fit statistics. There are six regressions, each named according to the type of spacecraft they apply to. Results for one of these regressions, including the plot and relevant details, are shown in Figure 8 and Figure 9 below.

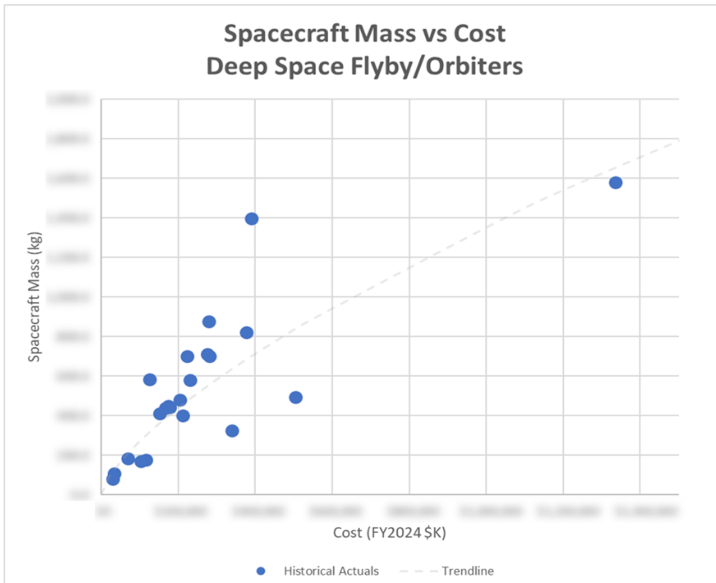


Figure 8: MERs for Visual Check

LogLinear Analysis for Dataset CAIV DeepSpc Flyby Orbit, DeepSpc FlyOrb LogLinear w Const

I. Model Form and Equation Table

Model Form:	Unweighted Log-Linear model
Number of Observations Used:	23
Equation in Unit Space:	[illegible]

II. Fit Measures (in Fit Space)

Coefficient Statistics Summary

Variable	Coefficient	Std Dev of Coef	Beta Value	T-Statistic (Coef/SD)	P-Value	Prob Not Zero
Intercept	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
cost_spacecraft_pmsemait	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Goodness-of-Fit Statistics

Std Error (SE)	R-Squared	R-Squared (Adj)	Pearson's Corr Coef	PRESS	R-Squared (Predicted)
0.3860	78.79%	77.78%	0.8876	3.9477	73.24%

Analysis of Variance

Due To	DF	Sum of Sqr (SS)	Mean SQ = SS/DF	F-Stat	P-Value	Prob Not Zero
Regression	1	11.6223	11.6223	78.0129	0.0000	1.0000
Residual (Error)	21	3.1286	0.1490			
Total	22	14.7508				

Figure 9: MER Details

This MER identifies a relationship between the mass and cost of a spacecraft characterized as a Deep Space Flyby/Orbiter. Within the dataset, 23 observations are grouped into this category, all of which are included in the calculated regression equation. These data points mostly fall close to the regression line, giving the MER an adjusted R-squared value that is sufficiently high, considering its purpose. The standard error value provides an additional measure of fit. This statistic is used to compute a prediction interval that shows the amount of uncertainty in an estimate generated by SMEC.

2.5 Interface Design

To enable ease of use, an intuitive interface for SMEC was created. The display includes a Read Me tab, which explains how the tool functions, and other tabs for input collection, methods implementation, and results. Along with numerical outputs, these results are presented via a series of graphical aids. For example, a pie chart illustrates the distribution of spacecraft cost between the first unit and subsequent units. Additionally, a pie of pie chart shows the proportion of the Mission Cost for Phase B-D that is designated to each element (if the spacecraft funding is estimated, rather than known). Examples of these charts are given in Figure 10 and Figure 11.

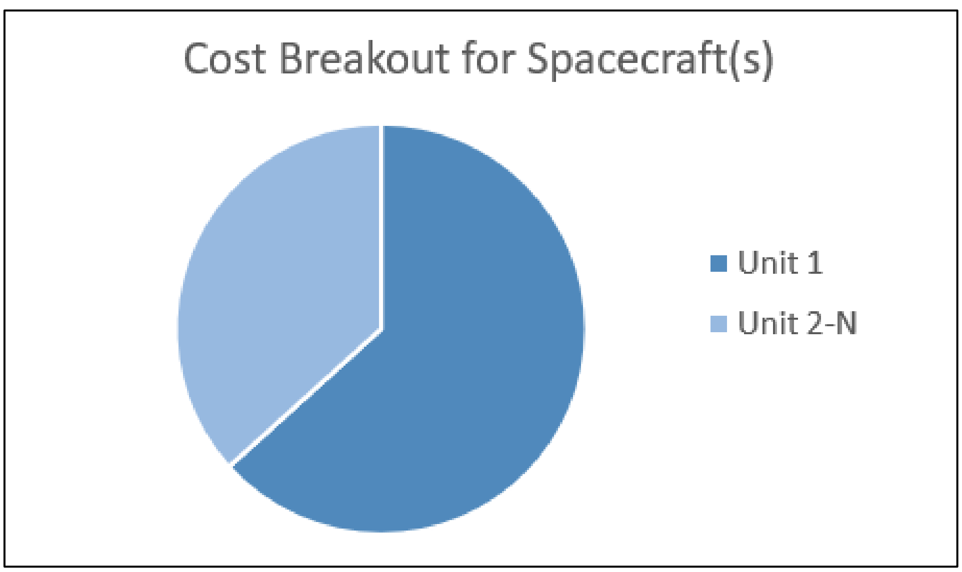


Figure 10: Cost Allocation by Spacecraft Unit (Example)

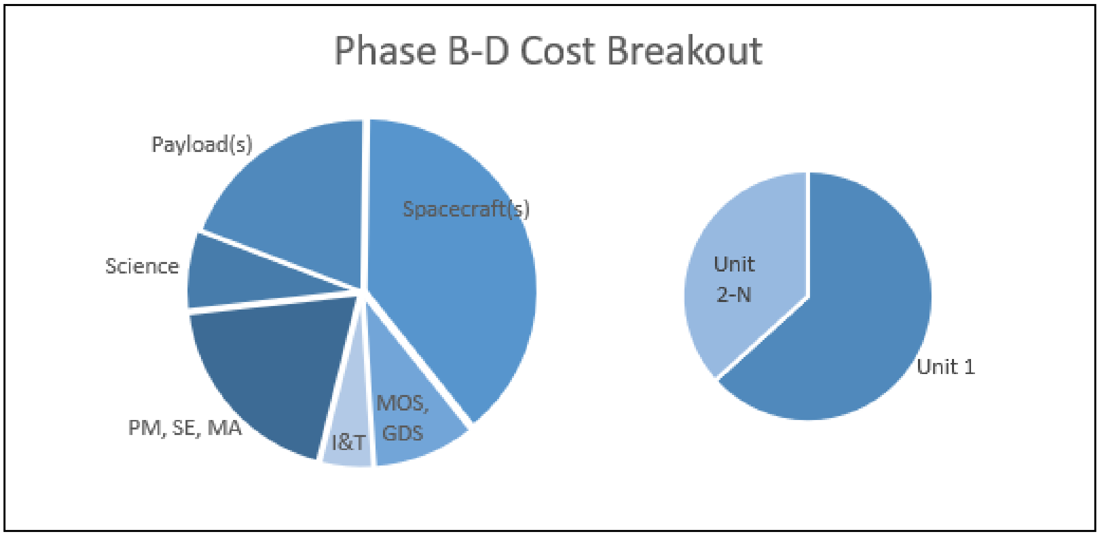


Figure 11: Cost Allocation by NASA WBS (Example)

An S-curve displays the range of estimated masses for the first unit of the spacecraft, accounting for the uncertainty within the MER. Several points on the curve are identified, including the Low (20th percentile), PE, High (80th percentile), and Target. An example of this graph is shown in Figure 12.

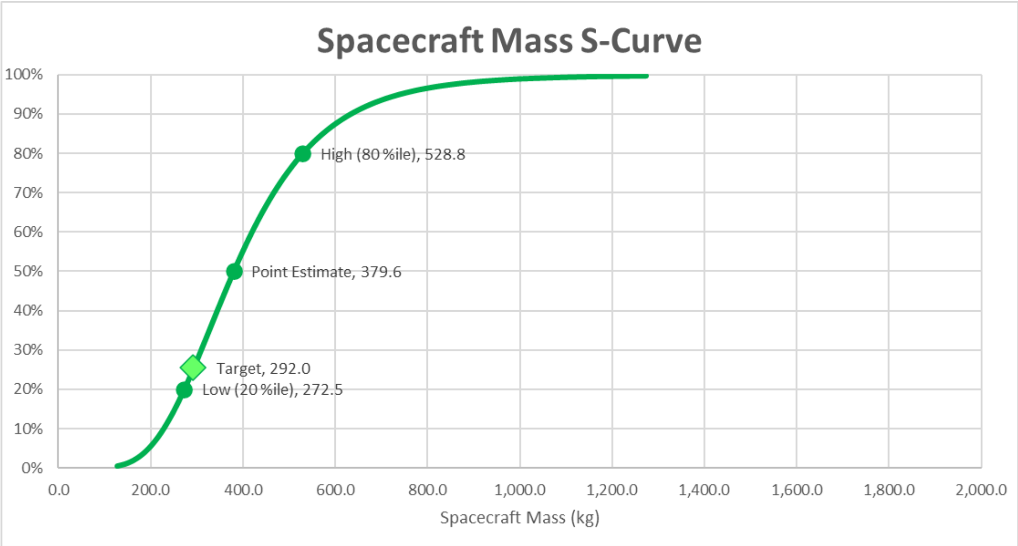


Figure 12: Spacecraft Mass S-Curve (Example)

A scatter plot displays a range of mass outcomes for the current mission (20th to 80th percentile) as a green line, amid points that represent historical actuals from the tool's dataset. A faint trendline, which illustrates the MER, is also included. An example of this plot is shown in Figure 13.

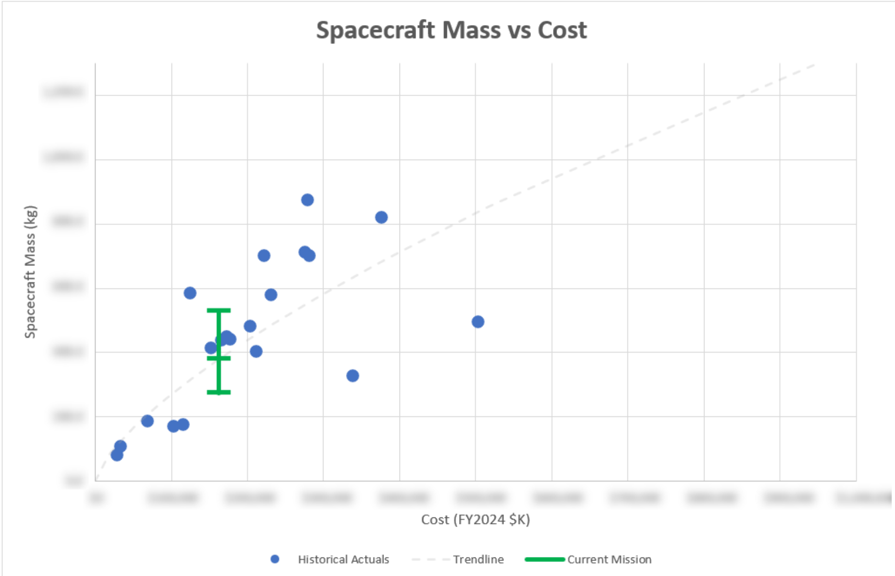


Figure 13: Spacecraft Cost and Mass Scatter Plot (Example)

Together, these visual representations paint a picture of the financial constraints on the spacecraft, the feasible masses considering these constraints, and the uncertainty surrounding those values.

CAIV Implementation

3.1 Supporting the Engineering Process

The CEMA Office has documented the process of developing SMEC so that other organizations can leverage a similar approach to build their own CAIV tools. Once created, these tools can be used to support spacecraft engineering studies. They are most impactful when applied during the "pre-work" period before the formal design process begins.

Consider an example scenario in which a proposal team approaches a Systems Engineer to request a point design for a spacecraft. This vehicle would be one of ten in a constellation surrounding the Earth, each of which would carry the same scientific instruments to take detailed measurements of a certain greenhouse gas. The spacecraft would all need to collect, store, and transmit large quantities of data, and to communicate with each other and the ground. These systems would enable the execution of a mission with a cost cap defined in a NASA AO.

The Systems Engineer collects all of these details and provides them to a Cost Analyst, who takes the steps identified in Figure 14.

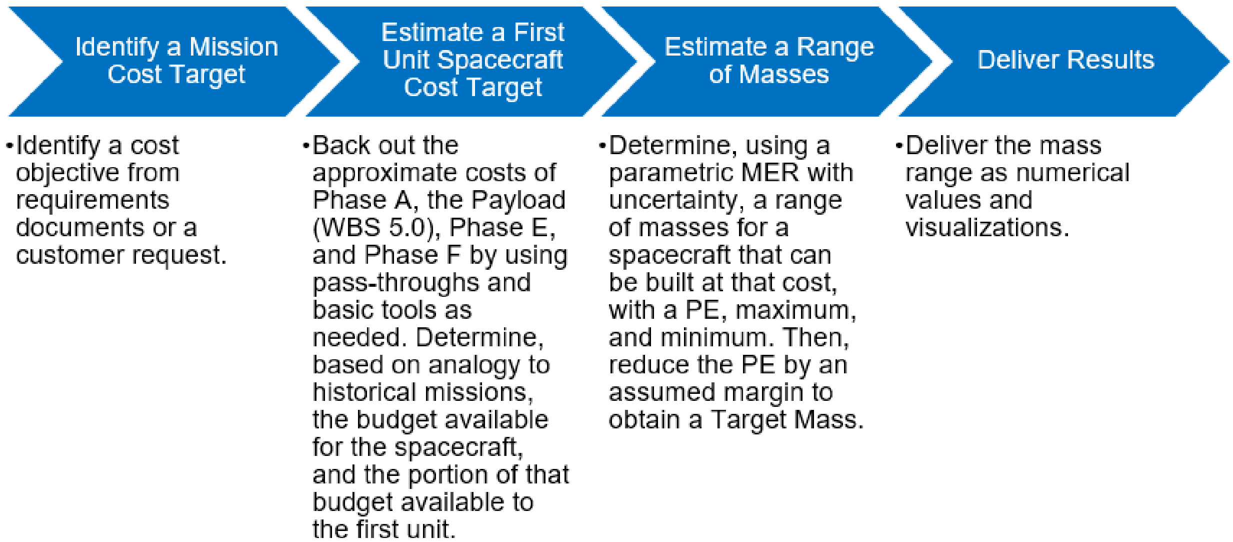


Figure 14: Applying CAIV to Support Engineers

Upon receiving results from the Cost Analyst, the Systems Engineer can communicate overall constraints to subsystem engineers to emphasize the importance of monitoring spacecraft size, or even designate specific mass limits to subsystems based on engineering judgment. They can also flag areas where cost/performance trade-offs are worthwhile and communicate these ideas to stakeholders. Alternatively, if the requested configuration is likely unworkable at a given cost, they can suggest modifications to the mission architecture (e.g., reducing the number of spacecraft in the constellation). These conversations can prompt certain cost-conscious decisions to be made before and during the design process, rather than after, when their implementation would require modifying the spacecraft. This minimizes the number of required design iterations by bringing an initial design closer to a reasonable cost, thereby reducing the time and effort spent by engineers over the long run.

3.2 Additional Applications to Spacecraft

While the value of running CAIV at the system level is clear, the applicability of this technique to spacecraft subsystems (e.g., GN&C) has not yet been explored. Subsystem-level MERs could be particularly beneficial to the design process. These relationships would enable a Cost Analyst to predict the relative cost impacts of adding a few kilograms to, or subtracting a few kilograms from, one subsystem compared to another. With this knowledge, it would be possible to answer questions that support trade-offs, such as:

> “*The total mass of our spacecraft is right at the limit of what has been affordable. To ensure the design satisfies the cost target, is it more important to optimize the size of the C&DH or Communications subsystem?”*
>
> “*If the Power subsystem mass is reduced by 10 kg, can the Structures mass be increased by more than 10 kg without making the system unaffordable?*”

These trade-offs, and others, are impactful throughout the initial design run and into later stages. The planned configuration of any complex system is likely to evolve over time as new technologies are contemplated and different components are compared. The shift occurs gradually through a series of decisions made at various junctures. These choices attempt to balance performance against other critical considerations (cost, schedule, risk, etc.) as studies are run and information becomes available. By establishing a clearly defined trade space that features cost, the CAIV approach provides immense value in this context. Several of its applications during a space project’s life-cycle are outlined in Figure 15.

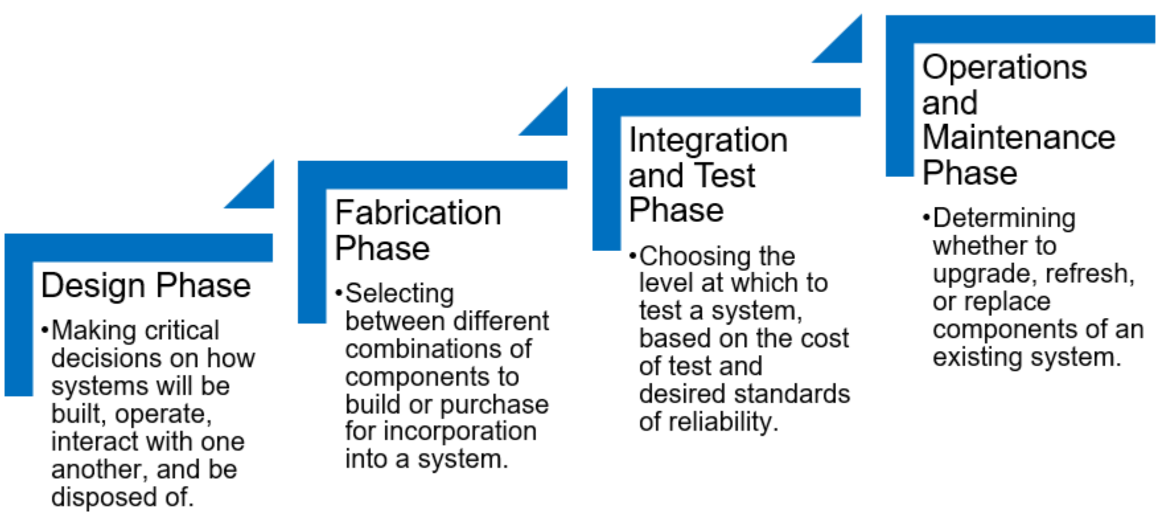


Figure 15: Cost/Performance Trade-Offs by Phase

3.3 Utility for Other Space Hardware

Beyond spacecraft, CAIV has applications to other types of space hardware. Consider the scientific instruments used by NASA. These devices often undergo extensive design, prototyping, and test, to ensure that they meet exacting standards of precision in their measurements. While some are novel, many have significant heritage, so relevant cost data is often available.

Notably, for some instruments, mass may not be the only appropriate parameter to limit. A magnetometer, for example, is a tool designed to measure the strength of magnetic fields. These instruments vary greatly not only in size, but also in their peak power requirement. Power is a parameter that can be controlled during the design process through deliberate decision-making, which makes it a strong candidate as a variable opposite cost in a CAIV regression. To demonstrate its utility, a limited dataset with cost, mass, and max power values for eight magnetometers was retrieved from a tool built by NASA's Jet Propulsion Laboratory (NASA JPL, 2023). This data was leveraged to create an MER and a Power Estimating Relationship (PER), the details of which are shown in Figure 16 and Figure 17.

LogLinear Analysis for Dataset Magnetometer CAIV Data, Magnetometer MER LogLinear 1

I. Model Form and Equation Table

Model Form:	Unweighted Log-Linear model
Number of Observations Used:	8
Equation in Unit Space:	[illegible]

II. Fit Measures (in Fit Space)

Coefficient Statistics Summary

Variable	Coefficient	Std Dev of Coef	Beta Value	T-Statistic (Coef/SD)	P-Value	Prob Not Zero
Intercept	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
cost_total	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Goodness-of-Fit Statistics

Std Error (SE)	R-Squared	R-Squared (Adj)	Pearson's Corr Coef	PRESS	R-Squared (Predicted)
0.7725	53.74%	46.03%	0.7331	6.4460	16.72%

Analysis of Variance

Due To	DF	Sum of Sqr (SS)	Mean SQ = SS/DF	F-Stat	P-Value	Prob Not Zero
Regression	1	4.1594	4.1594	6.9702	0.0385	0.9615
Residual (Error)	6	3.5804	0.5967			
Total	7	7.7398				

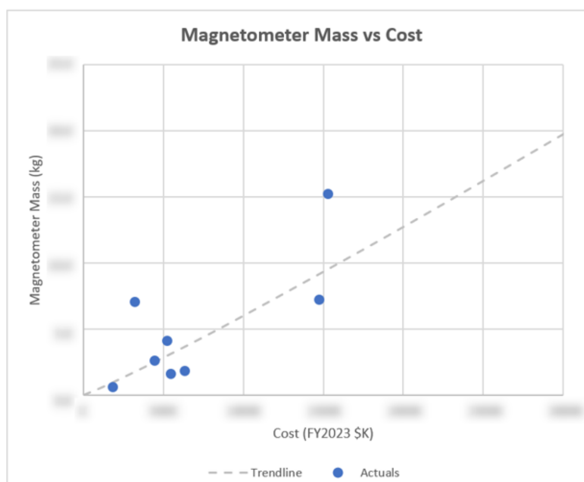
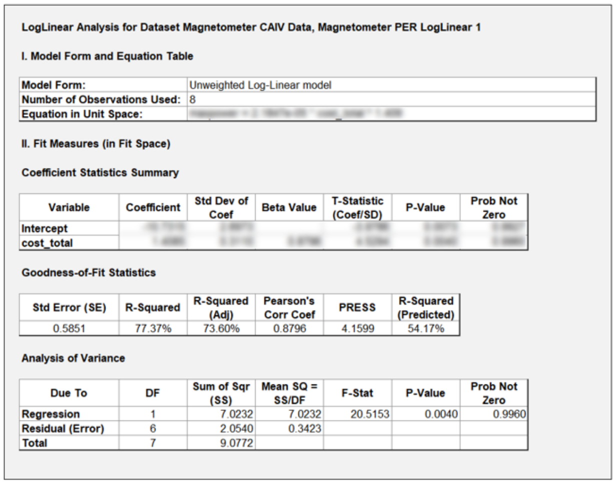


Figure 16: MER Statistics and Plot for Magnetometer



LogLinear Analysis for Dataset Magnetometer CAIV Data, Magnetometer PER LogLinear 1

I. Model Form and Equation Table

Model Form:	Unweighted Log-Linear model
Number of Observations Used:	8
Equation in Unit Space:	[illegible]

II. Fit Measures (in Fit Space)

Coefficient Statistics Summary

Variable	Coefficient	Std Dev of Coef	Beta Value	T-Statistic (Coef/SD)	P-Value	Prob Not Zero
Intercept	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
cost_total	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Goodness-of-Fit Statistics

Std Error (SE)	R-Squared	R-Squared (Adj)	Pearson's Corr Coef	PRESS	R-Squared (Predicted)
0.5851	77.37%	73.60%	0.8796	4.1599	54.17%

Analysis of Variance

Due To	DF	Sum of Sqr (SS)	Mean SQ = SS/DF	F-Stat	P-Value	Prob Not Zero
Regression	1	7.0232	7.0232	20.5153	0.0040	0.9960
Residual (Error)	6	2.0540	0.3423			
Total	7	9.0772				

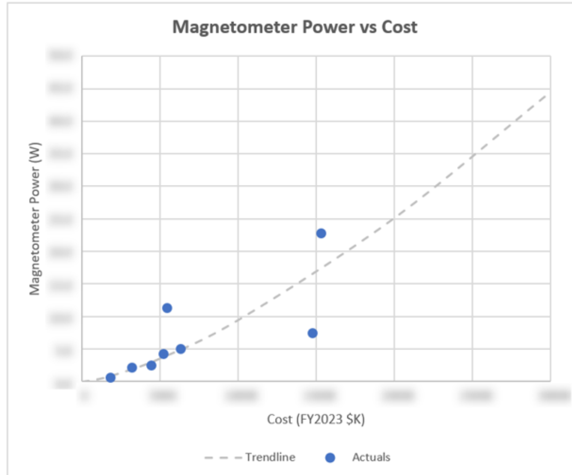


Figure 17: PER Statistics and Plot for Magnetometer

The use of MERs, PERs, and other relationships, can support the development of cost-effective hardware across many commodities that operate in various environments.

3.4 Limitations of the Approach

While useful, the CAIV approach is not without limitations. These restrictions are a function of the quantity of existing (i.e., legacy) systems that are similar to the new one being evaluated and the degree of similarity between the existing and new systems, as detailed in Figure 18.

Quantity of Similar Systems

Question: How many systems are of a similar type to the one being estimated?

Importance: A relative scarcity of similar system limits the number of observations that can be used to calculate of an estimating relationship (MER, PER, etc).

Example: A type of scientific instrument may have been sent to space many times before, like an imager or a space weather sensor. Or, the instrument may be one of only a handful of historical examples.

Limitation: If very few historical examples exist, it may not be possible to develop a credible estimating relationship. Any estimates generated using these formulas would have significant uncertainty.

Degree of Similarity Between Systems

Question: How similar is the new system to the ones that are considered a "similar type"?

Importance: A new system that closely resembles older systems can be predicted more reliably than a system that differs significantly from others.

Example: A spacecraft that falls into the category of Earth Orbiter may use high-heritage technology that has been flown many times previously. Alternatively, it may contain bespoke mechanisms, advanced communications hardware, or a propulsion system that requires significant new development.

Limitation: If the new system is not particularly similar to historical examples, it may be necessary to flag any estimates generated as potentially non-applicable.

Figure 18: CAIV Limitations

Conclusion

4.1 The Value of CAIV for Spacecraft

As the old, if over-used, truism goes: space is hard. Space is also expensive, and the hardware designed to travel through it is a significant contributor to the cost. As NASA and other agencies set loftier objectives, engineers will be required to develop more complex spacecraft, leveraging cutting-edge technologies to send more data from further destinations. Some of these technologies, such as Deep Space Optical Communications (DSOC), which uses lasers to transmit data from beyond the Earth-Moon system at a rate that is 10-100 times faster than radio communications, have already been demonstrated (NASA JPL, 2023). Others, such as the nuclear thermal propulsion system planned for a joint mission between NASA and the Defense Advanced Research Projects Agency (DARPA), are still in conceptual stages of development (Bardan, 2023). These technologies, along with others, will be implemented in spacecraft that enable the missions of the next several decades.

As the NASA CEMA Office has shown with SMEC, CAIV is an intuitive way to add cost as a consideration early in the process of designing new spacecraft. SMEC is built on an expansive set of historical data, which was used to develop analogy and parametric methodologies. While the analogy technique enables the leap from a Mission Cost Target to a Spacecraft Cost Target, the parametric MERs allow a user to estimate a range of affordable masses for a spacecraft based on its function and destination. This spread is shown numerically and visually, using pie charts, S-curves, and scatter plots that depict a planned spacecraft alongside other systems of the same type. Together, this package highlights cost-related challenges for an engineering team, equipping them to make design choices that bring system costs to, or at least close to, acceptable levels.

Outlining the relationship between cost and performance, and the limits on each, at the start of the design process enables engineers to consider these factors simultaneously. It provides a data-driven basis for assessing the feasibility of meeting performance and cost objectives and establishes a trade space where these variables can be traded off at key decision points. This equips engineers with the tools to communicate their expectations and concerns both internally (to their team) and externally (to stakeholders), with the number of iterations required to reach an affordable design.

4.2 Ideas for Future Work

The CAIV approach is most effective when applied both at the top level and at lower levels of detail. For spacecraft, this means identifying relationships between cost and performance parameters for the entire system and for individual subsystems. Understanding how mass, power, and other factors relate to cost in each of these areas reveals the most efficient places to tweak parameters (i.e., ones where cost can be reduced while impacting performance the least). This information is most useful when designing a spacecraft, but also has value as the system is assembled, tested, and even operated, as trade-offs can be conducted at every stage of a program's life-cycle.

Moreover, CAIV's utility can be extended beyond spacecraft to various other types of hardware. In terms of space equipment, it also applies to scientific instruments (such as magnetometers) and has been leveraged on launch vehicles (EELV). Other commodities to which it has been applied, historically, include communication systems (MIDS), missiles (AIM-9X and JASSM) and other ground- and sea-based systems.

Future work should aim to increase the depth of research on CAIV applications to spacecraft by examining relationships between cost and technical parameters for different subsystems. It should also expand the breadth of research on the technique, by exploring the benefits of its implementation on additional types of space hardware and other commodities. These efforts will come with challenges. To evaluate the connections between cost and parameters, expansive datasets that capture different variables will need to be collected and normalized. Data scarcity and variance in the data will present limitations, which must be recognized and communicated. Yet, despite the difficulties, the CAIV methodology should be applied more broadly given its potential to enable cost-conscious decisions that save time and money.

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Ryan Sukley is a Lead Cost Analyst at Technomics, Inc., with over 5 years of experience performing cost and economic analyses for the United States Department of Defense, the Department of Homeland Security, and NASA. Currently, he specializes in providing cost estimates for spacecraft and scientific instruments based on early design concepts, using a combination of parametric tools. He also supports the validation of various cost products for programs that are further along in their life-cycles. His passion for education has led him to build and deliver trainings on data management, data analysis, and risk and uncertainty. He is a former math and science teacher and holds a B in Economics from Franklin & Marshall College, along with an MS in Applied Economics from the University of Maryland.