An Analogy-based Method for Estimating the Costs of Spacecraft [1,2]

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Abstract—High-level parametric cost models are often used to obtain an estimate of spacecraft costs in cases where system details are unavailable, or in which multiple options are being studied. A previous study demonstrated the advantages of a method for estimating the costs of space-based instruments using the actual costs of a small number of analogous instruments. In the present study, a similar approach is applied to the estimation of spacecraft bus system and subsystem costs. Using The Aerospace Corporation's database of small satellite technical, programmatic, and cost parameters, several implementations of this analogy-based approach were tested, and the results were compared with estimates from several versions of The Aerospace Corporation's Small Satellite Cost Model. In all cases, the analogy-based method provided results comparable to good parametric cost models. Good results were also obtained when applying the analogy method at the bus system level with only two or three input parameters.

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1. INTRODUCTION

One method used for cost estimation of spacecraft is to apply parametric cost models developed from historical data. Parametric models can range from detailed component-level models requiring extensive knowledge of the system being estimated to simple dollars-per-pound rules of thumb. In this paper, the focus is on spacecraft bus subsystem and system-level models. This type of model would most often be used early in the design process when design details necessary for a component-level model or grass roots estimate are unavailable. They are also used in trade studies, when multiple options must be estimated quickly or later in the development cycle as a "sanity check" on more detailed parametric or grass roots estimates.

Another approach to estimating costs early in the development cycle is to base the estimates on the costs of a small number of similar, previously built spacecraft. If the system being estimated is closely related to previously built, analogous systems, this method could potentially give more accurate estimates than a broadly based parametric model. For example, manufacturers often feel that their unique processes are not well represented by an industry-wide parametric model. Selecting previous buses from the same manufacturer could alleviate this issue. Also, the estimator could more closely focus on a particular mission type such as Mars orbiters or Earth-orbiting communications satellites, instead of the broader planetary and Earth-orbiting mission classes typically used in parametric models.

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Kellogg and Phan [1] previously reported a method for performing analogy-based cost estimates of space-based instruments; this method showed improved accuracy compared to a high-level instrument parametric model. In this paper, the method is extended to the estimation of spacecraft bus system and subsystem costs.

For analogy-based estimates, costs from one or more past projects that are similar in complexity and objectives are used, based on the estimator's judgment that these projects are representative of the spacecraft bus to be estimated. This historical cost data is then adjusted to account for technical and programmatic differences between the historical bus and the bus to be estimated. In this paper, the adjustment is made using cost estimating relationships (CERs) from three versions of The Aerospace Corporation's Small Satellite Cost Model (SSCM).

2. SSCM Background

In the early 1990s, with funding from various DoD organizations, Aerospace developed CERs to estimate system-level costs of small satellites. From this work, the first version of SSCM was generated. In 1995, NASA provided funding for the first phase of an activity to develop a set of subsystem-level small satellite CERs. This work required obtaining a variety of mass, power, technical and cost parameters for numerous small satellites, along with impacts on cost such as schedule difficulties, funding interruptions, requirements changes, and cost-sharing among multiple contractors and led to the development of a set of CERs that could estimate the recurring and non-recurring costs of small satellite subsystems.

In the past few years, SSCM development has been funded by Aerospace internal research and development funds. The work has led to the inclusion of more recently launched small satellites, inclusion of interplanetary spacecraft, the introduction of risk-based estimates using NASA's technology readiness levels (TRLs) and other approaches, and the ability to spread small satellite development costs over a schedule. Since the first NASA delivery, multiple versions of SSCM have been released; the development of a version for 2004 is entering the final stages. A further discussion of SSCM can be found in [2] and [3].

"Small satellite" is a subjective term. In the context of SSCM, any satellite with a launch mass of less than 1000 kg is considered "small" and is eligible for inclusion in the database used to develop SSCM. This includes domestic, foreign, commercial, civil, military, operational and experimental satellites. SSCM data typically comes directly from the spacecraft bus contractors, and represents the actual technical and cost data for the bus only. It does not include any other program costs such as instruments or ground systems. The elements that are included in the estimate provided by SSCM are detailed in Table 1.

Table 1. SSCM Estimated Elements

Element	Description
Attitude Determination and Control System (ADCS)	Control electronics, attitude sensors (earth, sun, star, magnetometers, gyroscopes), actuators (torque coils, reaction/momentum wheels), and gravity gradient booms.
Propulsion	Tanks, thrusters, servo electronics, and propellant feed plumbing.
Power	Batteries, power control electronics, power converters, wire harnesses, and solar arrays.
Telemetry, Tracking & Control (TT&C)/ Command & Data Handling (C&DH)	Antennas, transponders, baseband units, receivers, transmitters, telemetry encoders/decoders, command processors, power amplifiers, signal and data processing equipment and magnetic or solid state data recorders.
Structure	Support structure for spacecraft and payload, launch adapter or deployment mechanism, other deployment mechanisms, and miscellaneous minor parts.
Thermal	Thermostats, heaters, insulation (tape, blankets), special conductors, and heat pipes. Does not include payload-specific cooling equipment.
Integration, Assembly & Test (IA&T)	Research/requirements specification, design and scheduling of IA&T procedures, ground support equipment, systems test and evaluation, and test data analyses. Typical tests include thermal vacuum and cycle, electrical and mechanical functional, acoustic, vibration, electromagnetic compatibility/ interference, and pyroshock.
Program Management/ Systems Engineering (PM/SE)	Systems engineering (quality assurance, reliability, requirements activities), program management, data/report generation, and special studies not covered by or associated with specific satellite subsystems.
Launch and Orbital Operations Support (LOOS)	Prelaunch planning, trajectory analysis, launch site support, launch vehicle integration (spacecraft portion), and initial on-orbit operations before ownership is turned over to the operational user (typically 30 days).

The analogy-based methods in this paper use versions of SSCM released in 1998 and 2002 (SSCM98 and SSCM02, respectively) as well as the upcoming 2004 (SSCM04) version. All three of these models provide estimates at the satellite bus subsystem level. A set of eight system-level CERs was also developed for SSCM98. These CERs, which require only two or three input parameters each, are also used in this paper.

3. METHODOLOGY

The methodology for using CERs to adjust the cost of analogous systems was described (for space-based instruments) in Kellogg and Phan [1]. The same methodology is used here, but applied to spacecraft bus systems and subsystems instead of instruments. The adjustment used for the analogy-based estimates is illustrated by Equation 1, where E is the analogy-based estimate, and C is the actual cost of the analogous system or subsystem.

$$E = C \times \frac{CER_{new}}{CER_{analogy}} \qquad (1)$$

The cost of the analogous item is adjusted by calculating a CER estimate for both the analogous item ($CER_{analogy}$) and the item to be estimated (CER_{new}), then multiplying the actual analogy cost by the CER estimate of the new item divided by the CER estimate of the analogous item.

Figure 1 provides a graphical representation of the adjustment process. The curve labeled "CER" represents a hypothetical CER for a single input variable. The vertical line represents the characteristics of the item to be estimated. Given the attributes of the estimated item, the CER would predict that the cost of the estimated system would be indicated by the "O" in Figure 1. The "+" in Figure 1 represents the actual characteristics and cost of a previously -flown, analogous item. By using the process described above, the cost of the analogous item is adjusted for the differences in characteristics resulting in the analogy-based estimate represented by the "X" in Figure 1. Ideally this process would be repeated for several analogies and the results combined by either a straight average or an average weighted by the confidence in, or applicability of, each analogy.

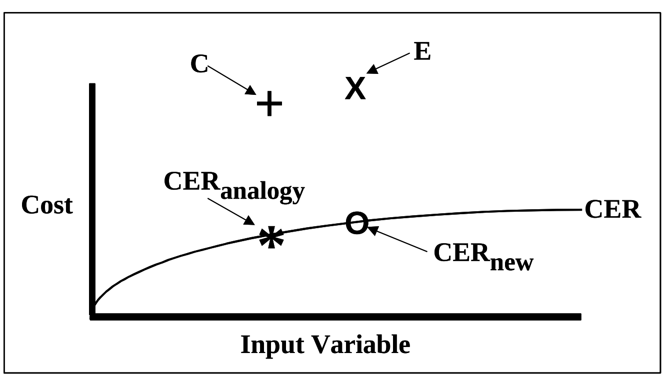

Figure 1. Illustration of the Analogy-based Estimate Methodology

4. VALIDATION PROCESS

The first step in the validation process is the selection of the validation data points. The spacecraft used as validation points represent a wide sample of the database, and are chosen according to the following rules:

- Spacecraft launched after 1990;
- Spacecraft that are not copies of previously flown buses;
- Spacecraft built by U.S. suppliers;
- Spacecraft for which the database contains all of the SSCM CER input parameters and complete cost data;
- Preference is given to spacecraft built by suppliers who have previously built similar types of spacecraft.

The final validation set consists of 18 spacecraft of several types, from several suppliers, that range in spacecraft bus dry mass from 88 to 582 kg. The selected points are listed in Table 2.

The second step in the validation process is the selection of the spacecraft to be used as the basis for the analogy-based estimates. The analogous spacecraft are selected based on all of the same rules as the validation spacecraft, with the exception of the preference for spacecraft built by suppliers who have built similar types of spacecraft before. The selections are made by first limiting the choices to Earth-orbiting or planetary, corresponding to the spacecraft to be estimated. Next, spacecraft built by the same supplier are given preference, followed by buses that were within 50% of the dry mass of the bus being estimated. In order to simulate the actual cost data available to an estimator, the launch dates for the analogy spacecraft are required to be earlier than the launch date of the validation point being estimated. For example, to estimate the cost of Mars Climate Orbiter (MCO), the analogies used were Mars Global Surveyor (also a Lockheed Martin planetary bus), NEAR, and Deep Space-1 (both planetary buses within 50% of the MCO dry mass). Table 2 also lists the spacecraft chosen as analogies. Most of the analogies are used for more than one validation point, and all but four of the validation points are used as analogies for other validation points. The number of analogies used per validation point ranges from one to five.

Not every subsystem is used for every analogy. Subsystems are eliminated from the calculation based on two criteria. If the subsystem is not used in the derivation of an SSCM04 CER, then it is not used in these tests. Reasons for exclusion include unique features of the particular subsystem or project that force it outside of the range of applicability, or incomplete subsystem data. Subsystems are also excluded if a parameter is significantly outside of the valid range of the CER used for the adjustment to the analogy cost. This reduces the number of analogies available at the subsystem level, but is consistent with the way an estimator would use the analogy data when developing an estimate.

Table 2. Validation and Analogy Data Points

Satellite Bus	Validation Point	Analogy Point
ACE	X	X
APEX	X	X
Clementine		X
DARPASAT(LIME)	X	X
Deep Space 1	X	X
EO-1	X	
FAST	X	X
GFO	X	X
Lewis	X	X
Mars Climate Orbiter	X	X
Mars Global Surveyor	X	X
MightySat 2.1	X	
MSTI 1		X
NEAR		X
SeaStar (Orbview-2)	X	X
Stardust	X	
STEP 0		X
STEP 1	X	X
STEP 2	X	X
STEP 3	X	X
SWAS	X	
TOMS-EP	X	X

5. RESULTS

5.1 Statistical Approach

The results of the validation process are characterized using two statistical metrics. The metrics use the differences between the estimates and the actual costs expressed as percentage errors. Percentage errors are used to prevent the results from the higher cost systems and subsystems from dominating the calculations. The percentage errors are calculated using the estimated cost as the denominator, and the difference between the estimated cost and the actual cost as the numerator.

The first metric is the Average Percent Bias (APB), which is an algebraic average of the percentage errors. APB can indicate if a method tends to over- or under-estimate the actual costs. APB is calculated as shown in Equation 2 where E is the analogy-based estimate, A is the actual cost of the validation spacecraft, and n is the number of validation points.

$$APB = \frac{1}{n}\sum\left(\frac{E - A}{E}\right) \tag{2}$$

The second metric is the Standard Deviation (SD) of the percentage errors. The SD is representative of the spread of the values of percentage error about the average value. This metric provides an indication of the range of actual costs possible given an estimate from a particular cost estimating method. The calculation of SD is shown in Equation 3.

$$SD = \sqrt{\frac{1}{n-1}\sum\left(\left(\frac{E - A}{E}\right) - APB\right)^2} \tag{3}$$

5.2 Subsystem Level Results

After all the data was selected and organized, the first calculations were performed at the subsystem level using the SSCM98, SSCM02, and SSCM04 CERs. The same CERs were then used to adjust the analogous costs to calculate the analogy-based estimates. The analogy estimates were averaged at the subsystem level and compared to the CER estimates.

The results at the subsystem level were generally in line with expectations. The APB for both the CER and analogy estimates was in the range from 0 to 15%, while the SD was typically in the 30 to 40% range. The published standard error of estimate (similar to the standard deviation) of SSCM CERs is also in the 30 to 40% range; therefore the results of this test appear reasonable.

Although the results vary widely by subsystem and even by SSCM version, the analogy-based estimates showed error statistics that were similar to the CER estimates. It was hoped that by choosing analogies that are more closely related to the system being estimated (as compared with the broad data set used to derive the CER), the estimates would be improved. Unfortunately this does not appear to be the case. It should be noted that the analogies were chosen at the system level, not the subsystem level. Although the satellites have similar missions and masses, there can be significant differences at the subsystem level. In future studies, it may be worthwhile to investigate the effects of choosing analogies at the subsystem level.

5.3 Subsystem Level Roll-up Results

The next step was to examine the results at the system level. For both the CER and analogy results, the system-level estimate was simply the sum of the subsystem estimates. A system-level estimate is only calculated when estimates are available for all subsystems. The one exception was for analogy-based estimates where there was only one subsystem with no analogy-based estimates available. In this case, the corresponding CER estimate was substituted for the missing subsystem analogy estimate and used to calculate the system-level analogy estimate. Table 3 shows the system-level results.

Table 3. System-level Validation Results (Based on Subsystem Estimates)

Subsystem Model	CER Estimates		Analogy Estimates		Number of Samples
	APB	SD	APB	SD	
SSCM98 System	2%	23%	4%	23%	8
SSCM02 System	1%	14%	10%	15%	10
SSCM04 System	3%	14%	7%	15%	9
Averaged System	7%	15%	12%	17%	13

As shown in Table 3, the system-level sum results for both the CER and analogy estimates are quite good. The three models (and the averaged values) all provide a set of system-level CER estimates with an APB of less than 10% and a SD of less than 25%. The analogy-based estimate results exhibited similar statistics. The "Averaged System" line was computed by summing the averaged subsystem estimates obtained by the three SSCM versions. If subsystem results could not be generated with some of the SSCM versions, only the available results were used–this is why there were more samples available for the "Averaged System" line than any of the other lines. Again it is noted that the analogy-based estimates do not show any advantages versus the CER estimates, although both exhibit excellent accuracy for many applications. With CER results of this accuracy, it may be unreasonable to expect the analogy-based method to provide significant improvement.

It is also noted that the system-level statistics demonstrated much better APB and SD values than the subsystem-level results. It is likely that differences in book keeping procedures are more prevalent at the subsystem level, and it is simply more reliable to compare costs at the system level. It is also likely that errors in individual subsystem estimates tend to balance out when combined into system-level estimates.

5.4 System-level Results

The final test was to look at the system-level results using the SSCM98 system-level CERs. This type of application is useful when cost or technical data is not available at the level of detail needed for the subsystem CERs. Table 4 shows the results of this test. The first column of Table 4 lists the types of inputs for each of the eight CERs. In all eight cases, the CER calculates a system-level estimate.

Considering the simplicity of the system-level CERs, the results are surprisingly good. Two of the CERs had APB values less than 10% and four had SD values less than 30%. The analogy-based estimates are even more impressive. Five of the CERs gave results with less than 10% APB, and four of those had SD values less than 35%. These results are only slightly worse than the system-level sums of the subsystem estimates, but are achieved with much less input data. The system-level CERs require only two or three input variables. It is likely that the strong performance of the analogy-based estimates is due to the selection of analogies at the system level and the application of system-level CERs.

Table 4. SSCM98 System-level CER Validation Results

System-level CER Inputs	CER Estimates		Analogy Estimates		Number of Samples
	APB	SD	APB	SD	
Comm.	46%	20%	12%	35%	17
Mass/Mission	6%	24%	7%	28%	17
Power/Mission	12%	28%	4%	34%	16
Attitude Control	40%	38%	0%	42%	16
Propulsion	-54%	60%	-19%	48%	10
Mass/Power/ Structure	17%	31%	4%	38%	17
Mass/Payload	4%	28%	3%	32%	17
Structure	13%	41%	10%	44%	17
System-level Average	25%	25%	11%	25%	17

5.5 Case Study

Although care was taken to select the best systems as analogies for the above results, the database did not always contain analogies that would be the first choice of the analyst. The following example uses a series of three buses in the same class from one manufacturer, which is the way the method would typically be applied. Table 5 shows the actual cost, bus dry mass, payload mass, and a CER estimate using the Mass/Payload system-level CER for three buses from the same manufacturer. The only inputs to the CER are bus dry mass and payload mass, and the CER over-estimates the costs of all three buses. This could be due to high heritage in the bus designs or perhaps manufacturer-specific processes that keep costs below an industry average level. Equation 4 illustrates the application of the analogy estimating method using the CER to adjust the costs of buses A and B to calculate an estimate of bus C. In this case, the analogy method predicts the cost of bus C to be $56M. The actual cost of $51M is less than 10% below the analogy-based estimate, which is a significant improvement over the 31% difference from the CER estimate.

Table 5. Case Study Parameters

Bus	Actual Cost (FY04$M)	Bus Dry Mass (kg)	Payload Mass (kg)	CER Estimate (FY04$M)
A	$53	589	205	$79
B	$66	596	298	$79
C	$51	551	245	$74

$$C_C = \left[\left(C_A \times \frac{CER_C}{CER_A}\right) + \left(C_B \times \frac{CER_C}{CER_B}\right)\right] / 2 \quad (4)$$

$$= \left[(\$53 \times \$74/\$79) + (\$66 \times \$74/\$79)\right] / 2$$
$$= \$56$$

6. CONCLUSION

A method for estimating the cost of spacecraft buses at the system-level and subsystem level using the actual costs of analogous systems and subsystems has been presented. At the subsystem level, the analogy-based method provided results comparable to parametric cost models. When the subsystem-level estimates were rolled up to system-level estimates, the results for both the parametric models and the analogy method were excellent. Finally, the application of several simple system-level parametric models produced results with better-than-expected error values. The use of these system-level CERs in analogy-based estimates produced additional improvements in the accuracy of the results, with several of the CERs producing error statistics only slightly worse than the roll-up of subsystem estimates.

These results demonstrate that the analogy-based method can be used in place of high-level parametric cost models with comparable results. In cases where it is felt that parametric models may not accurately reflect specific factors that are also present in previously built buses, the analogy method can be used with good confidence in the results. The analogy method using the system-level CERs provides a particularly useful method for estimating bus costs very early in the design process. For example, with just mission type and payload and bus mass and power, four of the system-level CERs could be used to adjust the costs of previously built buses, with the results averaged to provide an estimate. The findings in this paper indicate that the results may potentially be nearly as accurate as a subsystem level parametric model requiring significantly more input data.

Analogy-based estimating methods have now been tested for both instruments and spacecraft buses. In both cases, useful applications were identified and their statistical accuracy calculated. This type of procedure could be extended to other estimation problems, using the appropriate models e.g., other types of CERs, or even possibly Mass Estimating Relationships.

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