Developing Analogy Cost Estimates for Space Missions

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The analogy approach in cost estimation combines actual cost data from similar existing systems, activities, or items with adjustments for a new project's technical, physical or programmatic differences to derive a cost estimate for the new system. This method is normally used early in a project cycle when there is insufficient design/cost data to use as a basis for (or insufficient time to perform) a detailed engineering cost estimate. The major limitation of this method is that it relies on the judgment and experience of the analyst/estimator. The analyst must ensure that the best analogy or analogies have been selected, and that appropriate adjustments have been made. While analogy costing is common, there is a dearth of advice in the literature on the "adjustment methodology", especially for hardware projects. This paper discusses some potential approaches that can improve rigor and repeatability in the analogy costing process.

Nomenclature

$d_{i,j}$	=	distance metric between project i and project j
x^i_k	=	technical attribute k in project i
C^{new}	=	estimated cost for a new project
C^{anal}	=	actual cost for a previous project selected as an analogy
N^*	=	number of analogy projects selected
w_t	=	average wage rate, typically dollars per workyear at time t
K	=	number of attributes in adjustment mechanism
α_k	=	weighting factor the attribute k
λ_i	=	weighting factor for analogy project i

I. Introduction

Analogy cost estimation is recognized as a useful approach in preparing an early cost estimate for a new system or project when there is insufficient historical data to develop a statistically valid cost estimating relationship (CER), or insufficient information, time, or resources to perform a engineering ("grass-roots") estimate. An analogy cost estimate is also useful as a "sanity" cross-check against results produced by these other two methods. The basic idea behind the analogy approach is that when a new system has functional and performance characteristics similar to an existing one whose cost is known, the known cost can be adjusted to reflect programmatic and technical differences to develop a cost estimate for the new system. Analogy estimates can be made for whole projects or elements of a project. Even when some spacecraft subsystems are entirely new designs, often others are developed as improved versions of previously successful designs (i.e., heritage designs). If their costs are known, heritage designs can serve as analogy projects, subsystems, or elements. In developing the analogy cost estimate for the new system or system element, the analyst/estimator must develop and apply the appropriate adjustments.

The major limitation of analogy cost estimation is that it relies on the judgment and experience of the analyst/estimator to develop and apply those adjustments. Yet there is a dearth of techniques and practical advice in the literature on the "adjustment mechanism", especially for advanced technology hardware projects like space missions. This paper discusses some potential approaches that can improve rigor and repeatability in the analogy costing process.

My review of the literature revealed that a number of relevant cost estimation handbooks that discussed the analogy approach. The focus, however, was on the necessity of *documenting* the choice of analog project(s), the adjustment factors, and the cost estimate. For example, DoD 5000.4M (Ref. 1) states:

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> For estimates made by . . . analogy costing techniques, the rationale and procedures used to prepare such an estimates must be documented. This should include the cost experience used, and the method by which the information was evaluated and adjusted to make the current cost estimate. If an analog estimate is made using complexity analysis, the basis for the complexity analysis (including backgrounds of the individuals making the ratings), the factors used (including the ranges of values), and a summary of the technical characteristics and cost driving elements shall be provided.

The Department of the Army Cost Analysis Manual (Ref. 2) states similar requirements:

> The analyst must show the validity of the direct comparison. A variation to this methodology is to adjust the historical data to account for some variation in the proposed system, activity, or item. For example, if commercial vehicle data are used to estimate some aspect of a tactical vehicle, then the historical data might have to be adjusted to accommodate the impact of complexity or "militarization." It is very important that the analyst document the "adjustment technology" to show the applicability of the methodology.

No guidance or help is provided on how the create the adjustment factors, leaving room for the analyst/estimator to apply any number of reasonable judgments in the process.

In contrast, the FAA Life Cycle Cost Estimating Handbook (Ref. 3) devotes an entire chapter to analogy estimating. Here, the analyst/estimator is asked to provide three factors to be combined multiplicatively with the analogy project cost. The three factors are (1) a complexity factor, based on design and performance differences assuming no special miniaturization and manufacturing technology differences; (2) a miniaturization factor; and (3) a productivity improvement factor, based on improvements in technology (i.e., how much the "production function" has shifted). The inclusion of a miniaturization factor reflects concern for "stringent" mass and volume constraints on components and subsystems. That this factor has not played a role in space system analogy costing is curious since there is both anecdotal and hard evidence that miniaturization has a strong effect on the cost of planetary rovers, making very small ("nanorovers") rovers much more expensive per kilogram that larger ones.

The journal literature on analogy cost estimation was not voluminous and tended to deal more with software projects than hardware. The focus of many of these articles was on empirical/statistical tests of alternative techniques for developing analogy cost (or effort) estimates, and on quantifying the accuracy of the estimates. Software projects are typically characterized by a few variables, most notably source lines of code (SLOC), which are nearly always collected and available to the developing organization, so the existence of data sets for even a modest number of similar completed projects (20-30) makes some statistical tests possible. These journal articles were also useful in framing the methodological issues discussed in the next section. Lastly, some articles dealt with whether analogy cost estimation is best or worse than traditional cost estimating relationships (CERs). On this point, controversy remains since the empirical evidence is not conclusive either way.

II. Methodological Issues

In analogy cost estimation, three key methodological issues are: (1) determining which analogy projects are the most appropriate ones to use, (2) the number of analogy projects to include in the adjustment mechanism, and (3) what adjustment mechanism will be applied. There are also a number of process issues that organizations wishing to employ analogy estimation must address. These include building an analogy cost database and making it available to analyst/estimators, automating the process of generating an analogy estimate for a new project (tools), training in the use of these tools, reconciling the analogy cost estimate with other approaches (validation), and documenting how the analogy cost estimate was made.

A. Selection of Analogy Projects

The selection of analogy projects can be accomplished subjectively by the analyst/estimator, if the available set of projects is small and the choice(s) is (are), more or less, obvious. When that is not the case, the creation and use of a metric to describe the closeness of one project to another that relies on technical and programmatic attributes is helpful in finding the most appropriate analog projects.

When technical and programmatic attributes are continuous variables, a number of distance metrics have been discussed in the analogy cost literature.[4,5] The most popular ones are shown as Eqs. (1) through (4). The Euclidean distance in Eq. (1) is both normalized to the available data set and weighted by a set of external multipliers α_k. Normalization and weighting are attempts to balance the importance of each attribute. Normalization is useful in guarding against an overweighting of some attributes simply because of the units in which they are measured.

The distance metric in Eq. (2), often used in cluster analysis, is similar to the square of the Euclidean metric as can be seen from its Taylor expansion. The distance metric of Eq. (3) is known as the "city block" or "Manhattan" metric as it is the "walking" distance when confined to a n-dimensional orthogonal grid. Last, the Eq. (4) metric is called the Chebychev or maximum distance metric. For reasons cited above, both the city block and maximum distance metrics should be normalized.

$$d_{i,j} = \sqrt{\sum_k \alpha_k \left[\frac{x_k^i - x_k^j}{\max_i(x_k^i) - \min_i(x_k^i)} \right]^2 \Big/ \sum_k \alpha_k} \tag{1}$$

$$d_{i,j} = \sum_k \left[\ln \frac{x_k^i}{x_k^j} \right]^2 \tag{2}$$

$$d_{i,j} = \sum_k \left| x_k^i - x_k^j \right| \tag{3}$$

$$d_{i,j} = \max_k \left| x_k^i - x_k^j \right| \tag{4}$$

When technical or programmatic attributes are not continuous variables, but fall into discrete categories, then typically the contribution of that attribute is set to zero if they are identical in the two projects being compared, or set to one if they differ. Obviously, there is a need then to standardized the values a categorical attribute can take in any analogy database so that the correct calculation is made. For example, in the original database of space missions obtained for use in this paper, the terms *solar panel*, *solar array*, and *solar* were used to describe the main power source. An automated tool for comparing these entries might result in a mismatch. Another way of translating categorical attributes into numerical values has been suggested by Idri and Abran.[6] They propose developing and using a membership function from fuzzy set theory to go from a linguistic value, such as *high*, *medium*, and *low*, to a normalized numerical scale.

B. Number of Analogy Projects to Use

The number of analogy projects to use is a joint decision with the adjustment mechanism. With the small data set (<20 missions with complete technical and high quality cost data) currently available for analogy cost estimation of space missions, it is likely that there are only one to three good analogy projects.[†] However, when the number of appropriate analogy projects in a database is found to be large, as may be the case with software projects, the cost analyst can take advantage of this with the right choice of adjustment mechanism. The cost analyst must make a decision based on an examination of the available data.

C. Adjustment Mechanisms

In this section, I outline some possible adjustment mechanisms based on the number of analogy projects selected, N^*, and the number of attributes used in the adjustment, K.

1. $N^* = 1$ with $K \geq 1$

Pick the closest analogy project based on the selected distance metric, and scale the known costs up or down based on a function of the analogy project's and new project's K attributes.

$$C^{new} = f(x_k^{new} \cdots, x_k^{anal} \cdots) C^{anal} \tag{5}$$

One method for creating the scaling function is to run a standard parametric cost model for both the analogy project and the new project, and form the ratio. Kellogg and Phan[7] attributed this method to Bob Bitten when they applied it to space instruments using the Multivariate Instrument Cost Model (MICM), developed at the Goddard Space Flight Center. (See Figure 1.) Parametric cost models for space missions such as NAFCOM and JPL's PMCM would, of course, be used in place of MICM when estimating the cost of a new mission.

$$C^{new} = \frac{NAFCOM(x_k^{new} \cdots)}{NAFCOM(x_k^{anal} \cdots)} C^{anal} \tag{5'}$$

[†] To make a quick check of this based on the database of space missions used in this paper, I constructed several histograms of calculated distance metrics comparing a new project (not in the database) against projects in the database. The results did not contradict this assertion, which the reader may verify using the data in the Appendix.

This method has the advantage that one is not relying entirely on the credibility of the parametric cost model since it is being used only in a relative sense. It can also be applied when only a few of the parametric cost model's inputs are known since defaults can be substituted for those that are as yet undetermined. However, further experimentation is needed to check whether this adjustment mechanism is valid beyond instruments to full space missions.

2. *$N^* = 1$ with $K = 2$*

Pick the closest analogy project based on the selected distance metric, and scale costs up or down based on relative scope and complexity. This method has been applied by Stuhr on a space-based radar mission.[‡] Typically the method is applied at the lowest practical level of the WBS. Scope addresses quantity or size, for example, the number equipment design or assemblies. Complexity addresses how difficult the task is, for example, the stringency of technical performance requirements or lack of inheritance. Ultimately, scope and complexity rely on expert judgment, and quantitative measures to support or guide such judgments may not be available early in a new project.

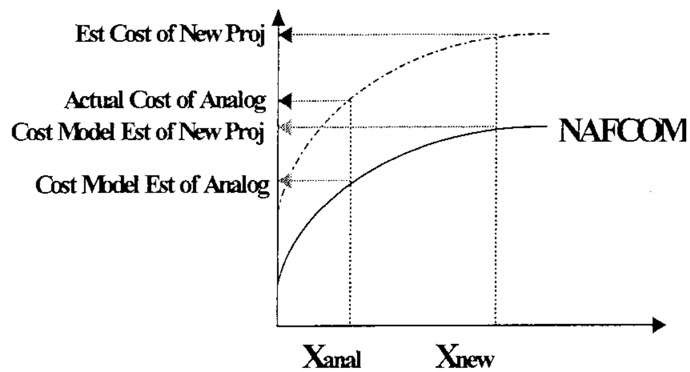

Figure 1. Bitten Analogy. *Though the use of NAFCOM (NASA / Air Force Cost Model) is shown, any parametric space mission cost model could be used to scale an analogy project's cost to estimate the cost of the new space mission.*

$$C^{new} = \left(\frac{x_{scope}^{new}}{x_{scope}^{anal}}\right)\left(\frac{x_{comp}^{new}}{x_{comp}^{anal}}\right)C^{anal} \tag{6}$$

3. *$N^* = 2$ with $K > 1$*

Pick an upper bound analogy project and a lower bound analogy project based on judgment, and scale costs in between based on a function of the analogy project's and new project's K attributes.

$$C^{new} = \lambda(x_k^{new}\cdots, x_k^{anal\_u}\cdots, x_k^{anal\_l}\cdots)C^{anal\_u} + (1-\lambda)C^{anal\_l} \tag{7}$$

One method of computing the weights is to use the distance metrics for the upper and lower bound analogy projects. Simple proportions (linear interpolation) could be used in which the lower bound project proportion is assigned to the upper bound project cost. Another set of weights could be formed that disproportionately favors the closer of the two projects, as in Eq. (7').

$$C^{new} = (\sin^2\theta)C^{anal\_u} + (\cos^2\theta)C^{anal\_l} \tag{7'}$$

where

$$\sin^2\theta = \frac{d_{new,anal\_l}^2}{d_{new,anal\_l}^2 + d_{new,anal\_u}^2}$$

A generalization of Eq.(7) would involve an arbitrary N^* and providing N^* - 1 weights located on a unit simplex.

4. *$N^* \geq 2$ with $K = 1$ for software project application*

Pick a set of analogy software projects and compute their average productivity in source lines of code (SLOC) per programmer per period. The estimated cost of a new project would then be given by Eq. (8).

$$C^{new} = w\frac{SLOC^{new}}{\bar{x}_{prod}(N^*)} \tag{8}$$

[‡] Private communication with Fred Stuhr, JPL Radar Science and Engineering Section, March 12, 2004

Typically the average productivity would be calculated from the analogy projects' SLOCs and costs. Wage rates serve to adjust the costs to account for inflation, if costs are in nominal dollars in the database.

III. Application

Whereas the last section discussed distance metrics and potential adjustment mechanisms in the abstract, the objective in this section is to describe some simple "experiments" that used real data from space missions to form an analogy cost estimate for a new mission. I obtained a database of actual costs, technical, and programmatic attributes for those JPL missions shown in the Appendix. The costs were already adjusted for inflation so all costs were in $FY04M. Technical attributes included spacecraft mass, launch vehicle, subsystem type, trajectory, and redundancy information. Programmatic attributes included phase durations, program type, spares and reliability class, and spacecraft developer information. The new mission (not in the database) was a nearly completed Mars orbiter project.

From these data, I first computed a variety of distance metrics, using three types of information that presumably would be available even in the earliest phases of a new project. The purpose of this was to determine whether a consistent closest analogy project would arise in this test case. Table 1 shows the attributes that were used for each distance metric, and the results are shown in the Appendix. Next, I performed an analogy cost estimate using upper and lower bound analogy projects to constrain the estimate. The results of these experiments are reported below.

k	Schedule	Mass	Target/Design
1	Phase A/B duration	Flight system dry mass	Target body
2	Phase C/D duration	Flight system wet mass	Parts class
3	Phase E duration		Main power source type
4			S-Band
5			Ka-Band
6			X-Band
7			UHF
8			Propulsion type

Table 1. Parameters Used To Build Distance Metrics. *Each of the parameters were normalized and weighted equally within their respective distance metrics. The design choices attributes were composed entirely of "categorical" parameters, which prohibited the use of the log ratio metric. Target bodies were represented by numerical values.*

A. Closest Analogy Project

The closest analogy project was not independent of the types of information used to compute the distance metrics. One might surmise that the closest analogy project would be another Mars orbiter mission; on this basis, the schedule-based metrics missed the mark, while the mass-based metrics performed consistently and as experience might suggest. The metrics based on target body and design choices tended to pick out the Mars missions, but the Chebychev version identified more than half the database projects as closest analogies. This is a consequence of using categorical attributes, which is not recommended in this case.

B. Estimating the Cost By Analogy

Since the mass-based distance metrics appeared to be consistent with judgment, I selected the Mars Orbiter mission as an upper bound analogy project and the Mars Odyssey (also an orbiter) as a lower bound analogy project. I computed the weights in Eq. (7) using both Eq. (7') and simple linear interpolation for each of the four mass-based metrics, and applied these weights to the actual cost of the analogy projects. The actual costs applied represented the full life-cycle costs (Phases A through E), though I could have chosen to estimate just Phase C/D costs. Table 2 shows the results. The simple linear interpolation performed better in this test case, though all estimates were within 20% of the actual cost of the new mission. The Euclidean distance metric performed uniformly better than the others, and in combination with the linear interpolation, produced a remarkably accurate estimate.

Weights	Euclidean	Log Ratio	City Block	Chebychev
Using Eq.(7')	1.132	1.197	1.192	1.186
Using Linear Interpolation	1.011	1.172	1.132	1.109

Table 2. Ratio of Estimated Cost to Actual Cost. *Results for different distance metrics based on flight system mass and different interpolation techniques are shown. The "actual" cost for the test case represents the nearly completed project's actuals-to-date plus an estimate of remaining cost, including reserves.*

IV. Conclusion

Far more experimentation, test cases, and data are needed to improve analogy cost estimation for space missions. From the test case involving an upcoming Mars orbiter mission, the distance metrics most aligned with judgment are those that combine simple mass attributes—flight system dry mass and flight systems wet mass. Those based on schedule did not perform well, and those based on design choices produced too many analogy projects. Some combination of mass parameters and design choices remains unexplored. In estimating the cost of the Mars orbiter mission using upper and lower bound analogy projects to bracket the cost, the Euclidean distance metric and simple linear interpolation did remarkably well. However, more work is needed to confirm whether this is repeatable.

Appendix

Distance Metrics Based On	Schedule Parameters				Mass Parameters				Target and Design Choices			
Mission Name	Euclidean	Log Ratio	City Block	Chebychev	Euclidean	Log Ratio	City Block	Chebychev	Euclidean	Log Ratio	City Block	Chebychev
QuikScat	0.327	1.688	0.556	0.235	0.203	0.537	0.041	0.036	2.236		8.000	4.000
Mars Global Surveyor	0.334	6.950	0.545	0.235	0.217	0.517	0.047	0.030	1.414		2.000	1.000
Genesis	*0.116*	0.159	*0.181*	*0.084*	0.329	1.724	0.108	0.064	2.000		4.000	1.000
Stardust	0.180	*0.155*	0.272	0.160	0.422	4.024	0.178	0.091	1.414		2.000	1.000
Magellan	0.267	0.512	0.378	0.196	0.158	0.289	0.025	0.024	2.449		7.000	2.000
Mars Odyssey	0.226	0.348	0.355	0.193	0.351	1.852	0.123	0.068	*1.000*		*1.000*	*1.000*
Mars Climate Orbiter	0.497	5.253	0.684	0.462	0.370	2.258	0.137	0.072	*1.000*		*1.000*	*1.000*
Jason 1	0.287	0.574	0.463	0.235	0.355	2.390	0.126	0.078	2.236		8.000	4.000
Cloudsat	0.368	1.060	0.572	0.319	0.222	0.712	0.049	0.044	2.236		8.000	4.000
Grace	0.233	0.211	0.352	0.210	0.173	0.343	0.030	0.027	2.236		8.000	4.000
Mars Pathfinder	0.458	3.495	0.540	0.454	0.217	0.659	0.047	0.042	1.414		2.000	*1.000*
NM Deep Space 1	0.463	3.857	0.500	0.462	0.386	2.857	0.149	0.080	2.000		4.000	*1.000*
SIRTF	0.416	1.001	0.625	0.300	0.232	0.787	0.054	0.047	2.000		4.000	*1.000*
Deep Impact	0.423	1.708	0.629	0.370	0.189	0.489	0.036	0.035	1.732		3.000	*1.000*
Mars Exploration Rover (MER A of 2 S/C)	0.334	1.040	0.482	0.311	0.183	0.450	0.033	0.033	1.414		2.000	*1.000*
Mars Polar Lander	0.476	4.221	0.677	0.437	0.332	1.912	0.111	0.070	*1.000*		*1.000*	*1.000*
Mars Observer	0.757	4.599	1.276	0.536	*0.105*	*0.061*	*0.011*	*0.008*	1.732		3.000	*1.000*
Cassini	1.003	2.939	1.666	0.765	0.992	2.049	0.984	0.496	2.449		7.000	2.000
Galileo	0.883	1.776	1.172	0.836	0.159	0.106	0.025	0.023	2.646		8.000	2.000
Voyager (2 S/C)	0.586	1.479	0.749	0.569	0.244	0.851	0.059	0.048	2.449		7.000	2.000
Infimum	0.116	0.155	0.181	0.084	0.105	0.061	0.011	0.008	1.000	na	1.000	1.000

Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The author wishes to acknowledge the support of JPL Costing Office and its manager, Robert Metzger.

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