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N95- 20741

COST ESTIMATING METHODS FOR ADVANCED SPACE SYSTEMS

by Kelley Cyr

NASA is responsible for developing much of the nation's future space technology. Cost estimates for new programs are required early in the planning process so that decisions can be made accurately. Because of the long lead times required to develop space hardware, the cost estimates are frequently required 10 to 15 years before the program delivers hardware. The system design in conceptual phases of a program is usually only vaguely defined and the technology used is so often state-of-the-art or beyond. These factors combine to make cost estimating for conceptual programs very challenging.

This paper describes an effort to develop parametric cost estimating methods for space systems in the conceptual design phase. The approach is to identify variables that drive cost such as weight, quantity, development culture, design inheritance and time. The nature of the relationships between the driver variables and cost will be discussed. In particular, the relationship between weight and cost will be examined in detail. A theoretical model of cost will be developed and tested statistically against a historical database of major research and development projects.

Cost Theory

In order to meet the needs of NASA for a long-range forecasting tool, the following requirements were laid down:

- Must have the ability to predict cost over long time horizons (25 to 50 years).
- Must be valid for substantially different of systems.
- Must be able to predict cost reliability despite significant technological advances.
- Require few inputs and be simple to use.

In order to determine the feasibility of a model that would meet the specified requirements, a proof of concept test was devised. A theoretical model was developed for predicting the total acquisition cost of a major hardware development program. The variables used in the model are described below.

Quantity Variable. The relationship between the quantity or number of units produced can take many forms. In Figure 1, four of the most common forms are illustrated. Figure 1a illustrates the unit or average cost method in which the average cost per unit is used. In this case, the average cost is the same regardless of the quantity produced. This method is most useful for small quantity buys of commercial products where the quantity purchased does not materially affect the cost of production.

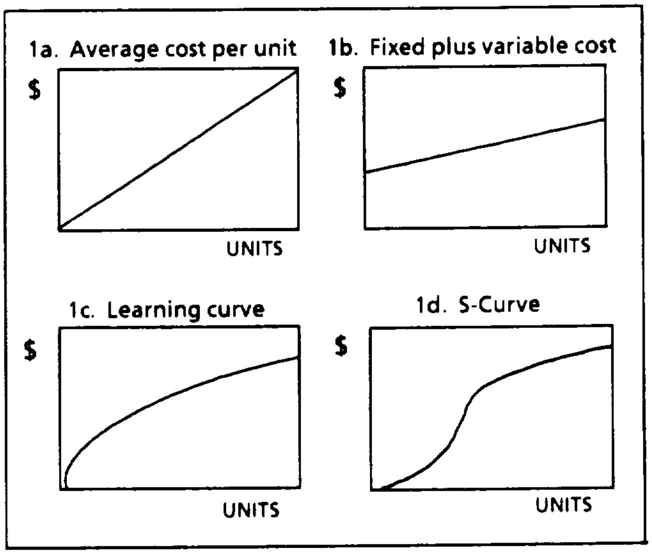

Figure 1. Total Cost Versus Quantity

A second method of estimating cost, illustrated on Figure 1b, is the fixed plus variable cost method. The marginal cost, in this case, is constant. The average cost is higher than the marginal cost, decreases as the quantity increases and approaches, but never reaches, the marginal cost. In this case, the fixed cost is relatively large and changing the quantity produced can substantially affect the average cost. This model represents increasing economies of scale.

The third method, illustrated in Figure 1c, incorporates the principle of decreasing marginal cost. In other words, the additional cost of each unit is slightly less than the previous unit. This principle is also known as the learning curve or experience curve. The learning curve also has decreasing average unit cost as the quantity is increased.

A fourth type of quantity relationship is shown in Figure 1d. In this case, the marginal cost increases for the first several units, then begins to decrease along the lines of a learning curve as quantity increases further. This example would represent a situation where the first few units were partially operational or low cost prototypes were gradually building up to full scale production articles. Once a reproducible configuration is reached, the marginal cost decreases according to learning curve principles.

Weight Variable. Weight has been used for many years in estimating the cost of aerospace systems. It is a most convenient variable since it generally characterizes the size and often, the performance of a piece of hardware. Weight is also a key engineering parameter; therefore, an estimate of it is usually available, even at the early stages of a program. Although the emphasis here is on weight, the discussion could also be applied to other descriptive parameters such as size, speed, power, etc.

The following discussion refers to weight as the dry mass of a single unit. Like quantity, weight can be related to cost in several ways. The most common relationships are depicted in Figure 2.

The simple cost-per-unit weight relationship is illustrated in Figure 2a. By definition, the cost-per-unit weight model has constant average cost-per-unit weight.

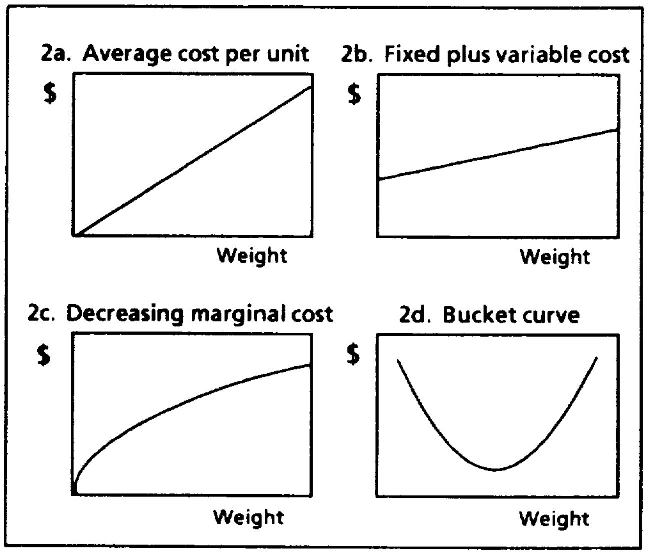

Figure 2. Total Cost Versus Unit Weight

The model in Figure 2b has the characteristic fixed plus variable cost. In this case, the average cost per unit weight decreases as the weight increases. The marginal cost is constant and average cost is asymptotic to marginal cost. This is a case of economies of scale with respect to unit weight.

Figure 2c illustrates a model in which the marginal cost is decreasing; hence, the average cost is decreasing. In this case, the rate of change in the marginal cost is also decreasing.

The total cost relationship shown in Figure 2c is an exponential growth function. The exponent happens to have a special meaning in economics: it is the elasticity of cost with respect to weight. If the elasticity is greater than 1, then the relationship is said to have decreasing economies of scale. If the elasticity is greater than 0 but less than 1, then there are increasing economies of scale. If the elasticity is exactly 1, then there are constant economies of scale.

Clearly, if there are strong economies of scale, it would be better to build larger (heavier) things. It should be noted, however, that weight and quantity may also be related. The larger something is, the less likely it is to be built in large quantities. The relationship between cost and quantity may also have economies of scale; therefore, the effect of different weights on both cost and quantity should be considered when estimating total program cost.

In the last case, Figure 2d, the marginal cost weight is negative up to a certain weight, then becomes positive. The total cost curve becomes U-shaped (also known as a bucket curve). This curve represents a situation where there is an optimum weight for a given type of hardware. Any attempt to decrease the weight below optimum would require additional cost through the use of exotic materials, additional manufacturing processes, or more complex fabrication techniques. By the same token, attempts to increase the weight above optimum would require additional cost for high performance propulsion, additional structural analysis and testing, specialized tooling, et cetera.

Culture Variable. So far, it has been postulated that significant relationships exist among cost, quantity and weight. It is not likely, however, that the relationships are exactly the same for all different types of hardware. A situation, such as the one in Figure 3, may exist where the cost versus weight curves for several types of hardware have the same elasticity but different multipliers. The culture variable is defined as a value representing the vertical height of the cost/weight curve for a given subcategory of hardware. If the cost weight curves were plotted on a log-log graph, the lines would be parallel straight lines and the culture variable would be a function of the vertical intercepts.

A category is defined as a group of hardware systems that are functionally similar; such as, aircraft, ship, or spacecraft. A subcategory describes a group of systems that perform a similar mission or have the same oper-

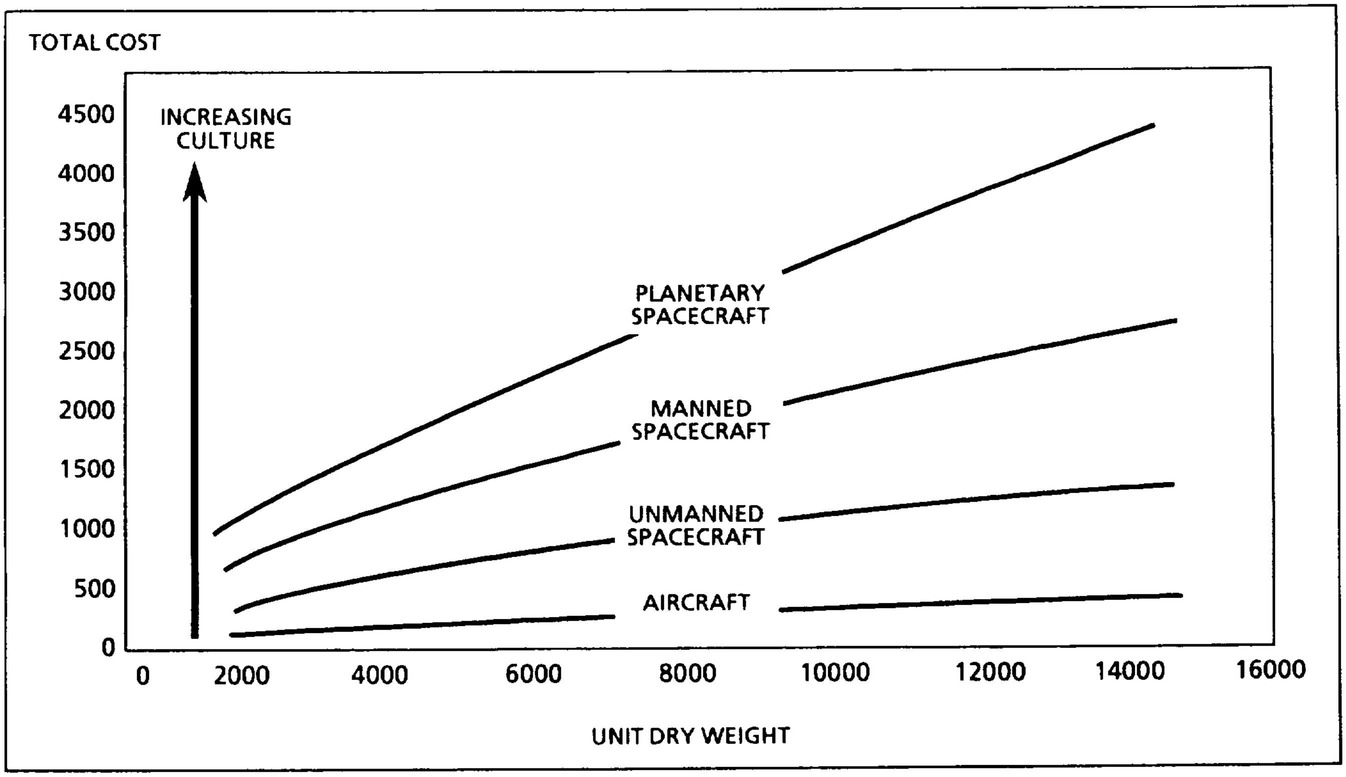

Figure 3. Culture Variable

ational environment. The subcategories of aircraft would include fighter, bomber, transport, etc. The classifications used in this paper are listed in Table 1.

It must be assumed, for the convenience of regression analysis, that the elasticities are the same for all subcategories. This will prove to be an overly restrictive assumption, and future work may focus on techniques to eliminate the need to make it.

Complexity Variable. Within a given subcategory, it is possible that the systems may vary considerably in terms of performance, capacity, level of technology, complexity of design, and many other factors. Variations of the type listed within a given subcategory are henceforth referred to by the variable name complexity. Complexity is obviously very difficult to define and quantify *a priori*.

The potential for overlap between culture and complexity can also create confusion. Research and development organizations tend to group along functional and mission lines; the classification scheme used for culture inherently contains organizational information as well. Organizational differences within a given subcategory may be included in complexity. Also, specification levels vary along the functional lines in platform, so only the specification differences within an established subcategory should be considered in complexity.

Since there is no readily available means of quantifying complexity *a priori*, this variable will not be used in the subsequent model derivation. It is discussed here in order to clarify the definition of culture and to provide a basis for future work to refine quantitative measures of complexity.

Table 1. Culture Classification Scheme

SUBCATEGORY	NO.	CULTURE	SUBCATEGORY	NO.	CULTURE
AIRCRAFT	**63**	**1.82**	**SHIPS**	**29**	**1.14**
ATTACK	8	1.96	A/C CARRIERS	5	1.11
BOMBERS	8	1.99	AMPHIB. ASSAULT	5	0.89
FIGHTERS	16	1.94	CRUISERS	4	1.19
FW-TRANSPORTS	10	1.63	DESTROYERS	5	1.25
PATROL	5	1.88	FRIGATES	3	1.14
ROTARY ATTACK	5	1.88	SUBMARINES	7	1.24
ROTARY CARGO	5	1.75			
TRAINER	3	1.46	**GROUND MOBILE**	**16**	**1.15**
COMMERCIAL	3	1.74	TANKS	4	1.24
			TRUCKS	7	0.82
MISSILES	**87**	**1.89**	APCs	2	0.96
AIR-AIR	13	2.04	RIFLES	3	1.59
AIR-ORBIT	1	2.04			
AIR-SURFACE	15	1.81	**SPACECRAFT**	**56**	**2.18**
ANTI-TANK	4	1.78	MANNED REENTRY	5	2.34
ICBM	11	1.92	MANNED ORBITAL	2	2.05
SURFACE-AIR	12	1.97	PHYSICS & ASTRONOMY	12	2.20
SHIP-AIR	9	1.74	EARTH OBSERVATION	6	2.04
SURFACE-SURFACE, LAND	8	1.88	WEATHER	7	2.19
SURFACE-SURFACE, OTHER	4	2.07	COMMUNICATION	9	2.22
ICBM (SUB)	4	1.89	MISC. SPACE	2	1.95
ROCKETS	6	1.64	PLANETARY	13	2.45
			UNMANNED REENTRY	7	2.04

Time Variable. Another factor that must be considered in estimating cost is the impact of time-related phenomenon. Inflation, productivity, technology and performance are just a few of the factors that may change with time. For most cost estimating applications, the effects of inflation are removed by applying standard inflation rates to convert the data to a constant-year dollars. The modeling of productivity, performance and technology change is not so easy.

Time-related phenomena may change at a fixed rate, like interest on a bond, or they may vary from one time period to another. The method of using a program milestone date as the time variable will result in a fixed rate of change when the model is estimated. Measurement of the variable rate case would require construction of an index, similar to an inflation index, and then selecting the appropriate index value based on the year of Initial Operational Capability (IOC), mid-point of construction or some other basis. A productivity or technology improvement index could be incorporated in this fashion. For this report, the IOC year was chosen to represent time.

Generation Variable. The design of a new aircraft, spacecraft or missile is often based on a previous design that has already been proven. A new airplane may use the previous airframe with only minor structural modifications. Spacecraft designs may use structural components, electronics, and mechanical systems already tested on a previous design. Designers may work with configurations they are familar with from previous projects. The result may be considerable savings in the development cost of new hardware. Savings can also be achieved in production since the tooling already exists and manufacturing experience is far down the learning curve from the previous design.

In theory, the cost of each subsequent model should be considerably less than the previous model. The amount of savings, however, would probably decrease as the series progresses. The total cost would be decreasing asymptotically to some level as shown in Figure 4.

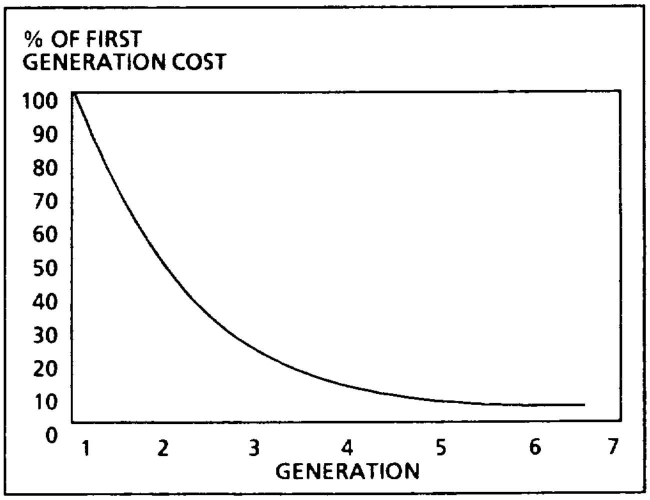

Figure 4. Generation Variable

The generation variable used in this paper is defined as the sequential number for a given model of a specific piece of hardware. Generation is not used to represent individual units of production, but rather a group of identical units. Subsequent generations must have very similar characteristics usually being produced by the same manufacturer or to the same specifications. Individual units of production may be given a generation number if they differ substantially from previous units but still retain the basic design and total production is small. All programs that do not have readily identifiable predecessors are given a generation of one.

Statistical Analysis

In order to statistically validate some of the theories relating to cost behavior, it was necessary to construct a database of cost and other variables for many different types of research and development programs. The database consists of 264 major programs. Most of the programs are U.S. Government sponsored. Many of the Government programs are defense-related weapons and delivery systems. A substantial number of NASA sponsored spacecraft are also included. A small proportion of the data comes from other Government agencies, foreign countries and commercial companies. In total, the database represents $1 trillion worth of expenditures in 1987 dollars.

Programs from the 1930s all the way up to the mid-1980s are included. Major categories include ground vehicles, ships, aircraft, missiles and spacecraft. Data collected for this study included top-level cost data, system weights, program schedule dates, developing organizations and technical data. A variety of sources were used to gather data, and information was confirmed by two or more sources whenever possible.

Model Evaluation. Model evaluation has consisted of three major steps. The first step was to test a model consisting of the variables quantity, weight, culture, IOC year and generation against the database as a whole. Step 2 required the estimation of models for individual subcategories of data. Finally, the elasticities derived from step 2 were compared to the culture variable derived in step 1.

Step 1 had several major functions. One was to evaluate the theoretical model of quantity, weight, culture, IOC year and generation. A second function was to produce estimated values of culture for different program subcategories. A third purpose was to identify any data observations that may be incorrect or classified wrongly. The final function was to develop estimates for the elasticities of weight and quantity, as well as other presumed constants.

Using total program cost, weight, quantity and other data, a multiple linear regression analysis was performed. The results are presented in Table 2. Out of 264 data points, 253 observations were included in the regression model. The remaining observations were rejected due to missing data. The dependent variable is the log 10 of total cost. The inde-

Table 2. Regression Model Results

Dependent Variable: Log_{10} of Total Acquisition Cost

Independent Variables:

		COEF. VALUE	T-STAT	STD. ERROR
Constant		-4.7645		
Q	Log_{10} Total Quantity	0.5773	47.5	0.0122
W	Log_{10} Unit Dry Weight (lbs.)	0.6569	43.5	0.0151
C	Culture	1.7705	31.8	0.0556
Y	IOC Year - 1900	0.0124	9.3	0.0013
G	Generation	-0.3485	-7.5	0.0466

Standard Error of Y Estimate	0.2247
R Squared	0.9125
Observations	253
Degrees of Freedom	247
MAPE	45%

$$\text{COST} = 0.0000172\,Q^{0.5773}\,W^{0.6569}\,58.95^{C}\,1.0291^{Y}\,0.4483^{G}$$

pendent variables are log 10, weight log 10, total quantity, culture, IOC year and generation. The coefficient of determination (R squared) is 0.91 and all of the variables are significant according to their statistics. Also, the signs and the magnitude of the coefficients are reasonable.

As discussed earlier, the culture variable is a derived value. The derivation begins by entering an estimated value for each culture subcategory. The multiple regression is performed using the original value for culture. The estimation errors for each subcategory is then adjusted by a factor calculated to make the average error for that subcategory zero.

A new multiple regression is then performed with the adjusted culture values. This process is repeated until the regression statistics stabilize. In order to minimize rounding errors, culture values are rounded at the second decimal place prior to the regression analysis.

A second regression analysis was done at the subcategory level for a few selected subcategories. This process generally used log 10 total cost as the dependent variable and log 10 weight and log 10 quantity as independent variables. In some cases, IOC year and generation were also included. The results of step two are summarized in Table 3. Note that the R-squared values are good for almost all subcategories. The elasticity of weight and elasticity of quantity are displayed along with estimated culture values.

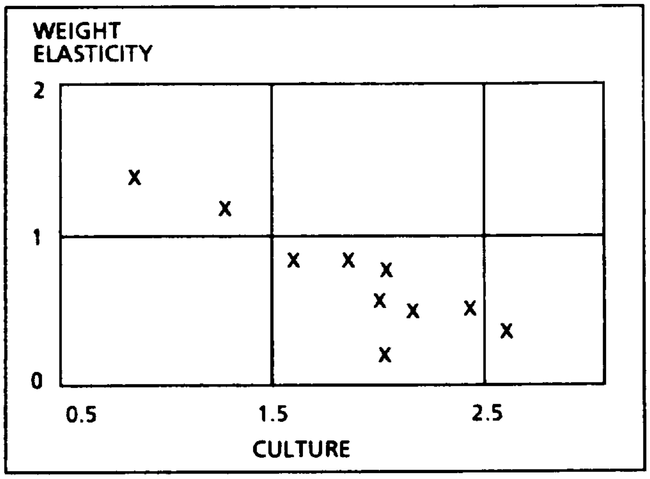

Figure 5. Weight Elasticity Versus Culture

The final step in the analysis was to compare the culture values to the elasticity values with respect to weight. Recall that culture is a function of the intercept of the regression lines and the elasticity is the slope of the regression lines in a log-log model. A regression analysis of the dependent variable weight elasticity and the independent variable culture found high correlation with an R-squared of 0.80, or 0.95 with the one outlier removed (see Figure 5).

Table 3. Subcategory Model Results

CAT	SUBCATEGORY	CULTURE	WEIGHT ELASTIC.	QUANTITY ELASTIC.	R^2
S/C	PLANETARY	2.52	0.45	1.02	0.87
S/C	PHYSICS & ASTRONOMY	2.31	0.68	1.17	0.95
MSL	AIR-AIR	2.06	0.69	0.53	0.86
MSL	ICBM	1.97	0.81	0.92	0.93
A/C	ATTACK	1.97	0.43	0.52	0.92
A/C	FIGHTER	1.96	0.74	0.46	0.95
MSL	AIR-GROUND	1.89	0.91	0.57	0.81
A/C	TRANSPORT	1.68	0.91	0.54	0.87
SHIP	SUBMARINE	1.33	1.18	0.92	0.99
SHIP	AMPHIB. ASSAULT	0.98	1.30	0.30	0.95

Furthermore, the coefficient of culture has a negative sign. This can be interpreted economically as meaning that high culture programs have greater economy of scale with respect to weight than low culture programs. Figure 6 illustrates the effect of the latter conclusion on the cost/weight curves. Note that moving down to the right increases the slope.

It is also noteworthy that two subcategories, submarines and amphibious assault ships, actually had weight elasticities greater than one, indicating diseconomies of scale.

An attempt was also made to correlate culture with quantity elasticity but the results were inconclusive. Of particular interest are the quantity elasticities of planetary, physics and astronomy satellites which are 1.02 and 1.17 respectively. The fact that these elasticities are close to or greater than one indicates that the marginal cost is constant or increasing. Since spacecraft generally have very small production runs, and the first few units are generally prototypes or test articles, this is not surprising. The high elasticities may be indicative of the S-curve depicted in Figure 1d.

Model Validation. A procedure was developed for validating the statistically estimated model. At the time this paper was written, only the phase one total database model has been tested. The validation procedure consisted of dividing the database into two parts. The data was divided at the median IOC year, 1969. All programs prior to 1970 were used to calibrate a new model using the same variables as the overall model. Values for culture were also calibrated based on the limited data.

The restricted model was then used to simulate a forecast of the actual programs in the second half of the database. The result was that the simulated forecast overestimated the total actual cost by approximately 45%. This indicates a bias in the estimating model. An examination of the coefficients showed that all were reasonably consistent between time periods except for the coefficient of IOC year. The coefficient for IOC year is 50% higher in the first period than

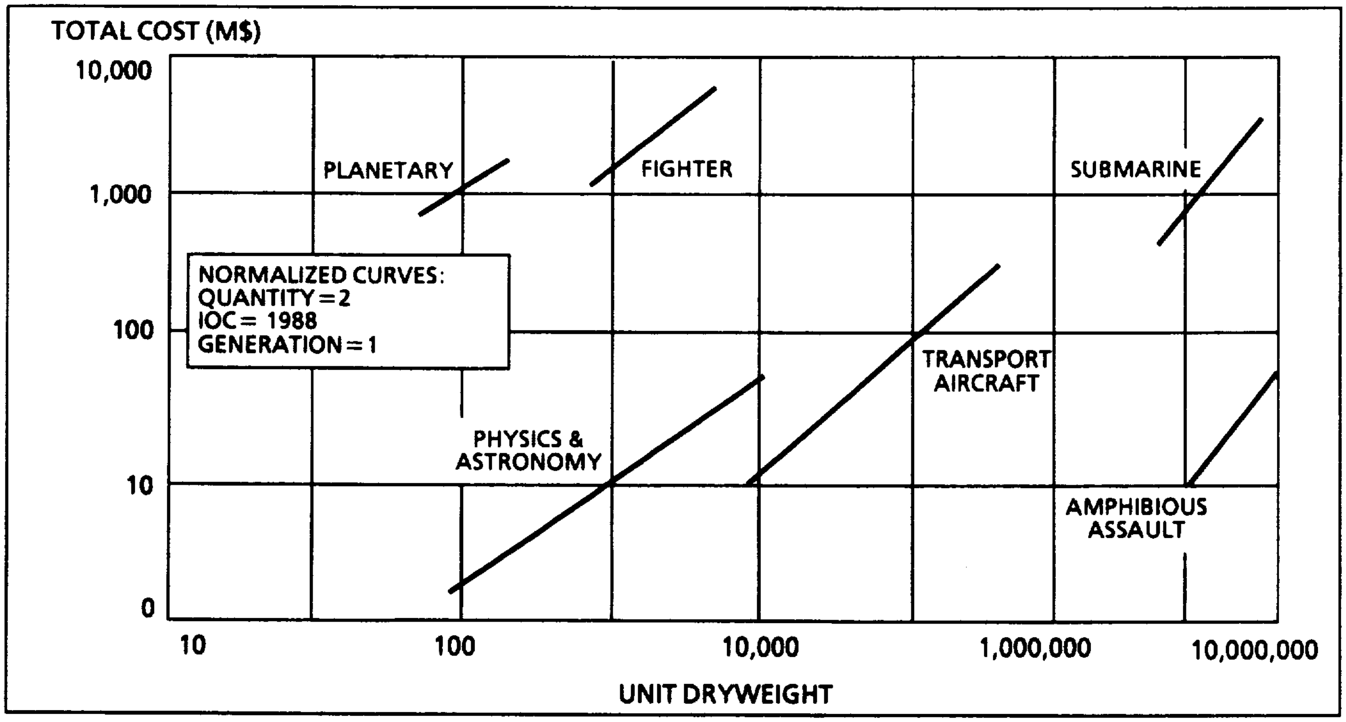

Figure 6. Subcategory Models

overall. This difference probably accounts for most of the overestimate. Several explanations may be offered for the variation in IOC year coefficients. Different inflation indices were used to normalize the data during different time periods. The indices used may not have been appropriate.

The IOC year variable used for time assumes a constant rate of change over the entire time period. It is possible that whatever factor the IOC year variable is attempting to measure was, itself, changing over time. Productivity changes in the work force are one possible explanation. Due to the magnitude of the error caused by the IOC year coefficient, it will be essential to identify the source of error before this model can be used for forecasting. Future work will focus on isolating the problem and developing solutions.

Conclusions

In order to accurately make any forecast using mathematical or statistical modeling, several conditions must be meet. First, the structure of the model; i.e., the nature of the relationships, must be identified. Second, the parameters of the equation that are expected to vary, as input or outputs, need to be specified. Third, those factors that remain constant must be identified and estimated. Finally, the conditions under which the structural equations and parameters remain stable must be specified and tested. Only when thorough testing has indicated stability and accuracy over the expected range of forecasting requirements can a model be put to operational use.

The model identified in this paper is a fair predictor of general hardware development cost. As such, it proves that using many varied programs as a data base for estimating a cost model is a viable concept. The use of many data points from different technology domains has several advantages. First, it increases the number of degrees of freedom in the statistical analysis which allows more explanatory variables to be used.

Second, the wider range of data available provides a deeper insight into the nature of the relationship between cost and various program factors. For example, a limited analysis of spacecraft data may have led to the conclusion that quantity elasticities are always greater than unity. In fact, production economies of scale should be achieved once the initial prototype stage is passed.

Third, a model based on a wide range of technologies should be more suitable for estimating the cost of new designs that may have no historical analogies. Finally, validating the model over different time periods may improve the confidence in estimates made far into the future. The model described here demonstrates that such a model can be constructed and will estimate cost within fairly reasonable bounds.

In addition, several economic conclusions can be drawn from the data model. The analysis shows that significant economies of scale with respect to weight exist for nearly all types of development hardware. The more complex the hardware, the greater the economies of scale. Also, the lower the weight of a subcategory, the greater the economies of scale are for that subcategory. Some classifications, such as ships, even have diseconomies of scale with respect to weight. The estimated elasticity of cost with respect to weight ranges from 0.43 to 1.30 with an average values of approximately 0.65. Economies of scale with respect to unit quantities also are evident. The range of estimated elasticities is very wide, from 0.3 to 1.17 with the average around 0.58. Some types of systems have diseconomies of scale. These are mostly very low production quantity systems such as spacecraft. The conclusion is that a modified learning curve such as Figure 1d may be appropriate.

The use of a culture variable was proven effective for combining different technologies in the same database. A methodology for deriving a quantitative measure of culture was presented and shown to produce good results. For future space developments, culture may be the most significant variable the cost analyst has to select. Weight and quantities will usually be given, but the particular hardware may not fall into any of the historical subcategories. It may also be possible to estimate culture for future programs using deterministic methods, such as a function of the ratio between weight and quantity. Another possible method of estimating new cultures would be interpolation or extrapolation of existing cultures.

The inclusion of a time-based variable causes the effects of time to be removed from the other variables in the model. The model could be used for long range planning if the future effect of time could be predicted. It was found that the cost of programs is increasing with time, even after the effects of inflation are excised. The time-related cost growth is not at a constant rate. The magnitude of cost growth appears to be from 0.0 to 3.0 percent per year. The exact nature of this time-related phenomenon is not yet understood, although it is believed to be combination of increasing performance, complexity and technology offset by improving productivity and development methods.

Finally, the benefits of design inheritance were clearly demonstrated. Substantial reductions in cost from using existing designs rather than starting from scratch are evident from the large negative coefficient of the generation variable. Cost savings of about 22 percent for each subsequent generation are predicted by the model. This fact has been used to great advantage on military acquisition programs and should be incorporated whenever possible in the space program.

The model does have some deficiencies. Most of the problems result from the wide range of estimated coefficients for subcategory models as shown in Table 3. The model of all data must effectively average these coefficients, which results in errors at the subcategory level. In addition, it was found that the modeling of time-related behavior (e.g., inflation, productivity, technology, etc.) is inaccurate. The model assumes that the rate change is constant but, in reality, it varies.

The combination of these two deficiencies makes the specified model unsuitable for long-range estimates of advanced space programs. Although the basic technique demonstrated here is sound, it must be refined even further to produce acceptable cost estimates. The specific weaknesses of the model have been identified and potential solutions will be implemented in the future.