New Directions in Automated Spacecraft Cost Estimation

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This paper sets forth in summary form a financial analysis and cost modeling results obtained from examining eight unmanned lunar and planetary spacecraft programs. The paper differs from the popular method of estimating total project costs by forecasting dollars, and comes to the conclusion that cost forecasting can be improved by selecting manhours as the basic cost unit. To develop this theme, the authors analyzed nearly 5000 spacecraft cost elements spread across 327 prime and subcontracts. A nonrecurring and recurring cost model was then constructed. The results of this research along with comparative cost forecasts are reported. On the basis of the analysis, the following conclusions were deduced: 1) Manpower is a homogeneous and standard unit across lunar/planetary progress. 2) Manpower has been found to be the cost driver in lunar and planetary programs. 3) Manpower analysis provides management with more insight in analyzing estimated and on-going projects. 4) The effect of learning and inheritance can be analyzed and measured better in terms of manpower.

Introduction

THE U.S. space program has passed through its early formative years and is now starting to mature as it enters the Shuttle Era. No longer is it sufficient merely to perform inspiring feats of human and technological achievement, but these must now be performed cost effectively within the available resources. As Tischler[1] points out in a recent *Astronautics & Aeronautics* article, the concept of the Space Shuttle as a low-cost transportation system must be paralleled with an effort to reduce the cost of developing and operating space payloads. Commensurate with achieving the goal of low-cost space utilization is the burden of planning and control placed upon NASA. That is, the ability to estimate accurately the cost of future space missions before a specific program commitment is made and then to be able to maintain expenditures in line with the budgetary estimates. The purpose of this paper is to address the problem of cost estimation from a new viewpoint and methodology in financial analysis and modeling.

Historically, early estimates of automated spacecraft projects have been considerably less than the final actual costs. Although project costs are obviously difficult to forecast at the pre-Phase A stage, the past record is somewhat dismal. The ratio of actual to estimated cost has been as high as 4:1, although a 2:1 ratio is perhaps more typical of early estimation performance. Among the apparent reasons for unreliable estimates are: 1) new technology barriers not clearly appreciated; 2) uncertainty and change in spacecraft/mission definition; 3) prevailing low-bid philosophy; 4) inadequate data base for cost modeling purposes and bid evaluation; and, to some extent, 5) inflationary factors.

Throughout the 1960's there was an increasing awareness within NASA that improved confidence in cost estimates must be achieved. In response to this need, cost estimation models have been developed by the Rand Corp., ITT Research Institute, General Dynamics, Martin Marietta Corp., Planning Research Corp., and Aerospace Corp., among others.[2-7] In addition, each of the NASA centers have improved their internal estimation techniques, and a number of studies have been undertaken to examine specific aspects of spacecraft project costs. This trend has continued into the 1970's and culminated in the extensive study of "payload effects" by Lockheed[8] and the opportunity, as expressed by them, to initiate a payload revolution using standardized low-cost designs.

In most previous modeling studies, the basic parameter used to estimate project costs has been dollar expenditure. Since so many variables contribute to dollar cost (including inflation, overhead rates, materials, subcontract fee, etc.) it is our contention that dollar expenditure is not the most appropriate parameter to use in modeling nor is it the most diagnostic of the development effort. A basic premise of the analysis presented here is that cost forecasting can be improved by selecting manpower (specifically direct labor hours) as the basic cost unit.

To develop this theme, the authors have obtained and analyzed (through work supported under Contracts NASW-2114 and NASW-2494) an extensive data base over eight lunar and planetary projects—Surveyor, Lunar Orbiter, Mariners' 64, 69, and 71, Pioneer F/G, Viking Lander, and Viking Orbiter. The trends established in the financial analysis along with the manpower/cost model constructed thereof should have general applicability to other automated payloads and should prove useful to NASA in their planning function. Although the study has, of necessity, dealt with "historical" project data, the methodology could serve as a baseline or reference case for estimating future project costs in the coming shuttle-era lifestyle.

Data Collection

It was recognized early in the data collection process that NASA Headquarters and Centers did not carry the financial details of project costs required in the analysis. Contacts were thus made with prime contractors through NASA Center authorization, and ultimately with subcontractors when necessary. The cost data supplied was in a form that permitted analysis below the subsystem level and allowed for the adjustment of subsystem definitions to ensure compatibility among different projects. The data profile consisted of a financial breakdown structure which listed cost accounts associated with a given spacecraft cost element. Such accounts generally consisted of wages, salaries, rental services, tooling, material purchases, etc. Data were then acquired on the direct labor hours (DLH) charged to each spacecraft cost element by

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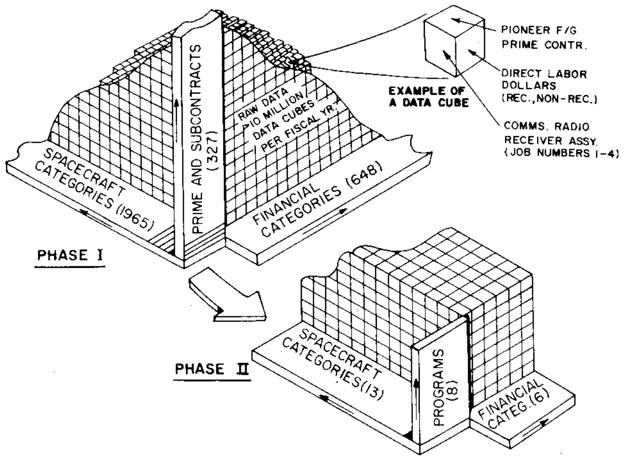

Fig. 1 Financial data analyis.

Table 1 Major project categories

Spacecraft subsystems	Technical support
Structure	Program management
Propulsion	Systems analysis & engineering test program
Guidance & control	Test program
Communications	Quality assurance & reliability
Power	Assembly & integration
Science experiments	Ground equipment
	Launch & flight operations

engineers, scientists, technicians, administrative and manufacturing personnel, and clerical workers. One recognizes that direct labor hours and direct labor dollars are essentially perfectly correlated in each cost element via the appropriate wage rate.

Raw data obtained over the eight projects consisted of 648 financial categories and 4843 spacecraft cost elements spread across 327 prime and subcontracts. In total, some 11.5 million expenditure items (data cubes) were examined including manpower, overhead material, and ancillary costs. These accounted for 99.7% of the actual total of $1.65 billion expenditure for these eight projects. Figure 1 shows schematically the phased process of data analysis and contraction to a manageable form for modeling purpose.

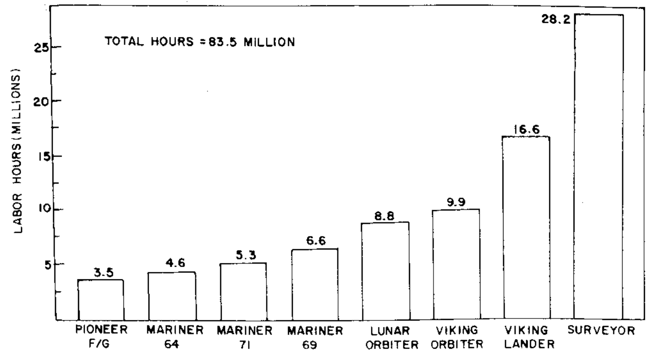

Fig. 2 Project hours summary (missions).

Initially, the 4843 cost elements were coarsely filtered into a reduced number of 1965 elements. Phase II involved recategorization into 624 line items comprising the 8 projects, 13 spacecraft and technical support categories, and 6 financial categories. Average data contraction between Phase I and II analysis is 18000:1. The analysis has shown that the Phase II matrix has an average resolution or cost visibility better than 0.1%; this could not have been achieved by listing coarse project data directly.

The 13 major project categories are divided into 6 hardware or subsystem areas and 7 technical support areas in Table 1. Space does not permit a detailed glossary of each major category but they do follow generally accepted definitions. Possible exceptions to the categories are: 1) mechanisms, thermal control, cabling, and pyrotechnics included in the structure subsystem; 2) aerodeceleration components included in propulsion rather than structure; and 3) the power subsystem in the case of RTG application, including batteries and conditioning equipment, but not the cost of the RTG units charged to NASA.

Manpower as a Modeling Parameter

The most immediate result of this analysis was the considerable insight it gave into where the money is actually spent in a space project. In addition however, it was recognized that the rigidity of the government accounting system was extremely beneficial in analyzing data over a range of projects spanning 15 years. The common denominator of the NASA cost reporting system is the cost incurred in direct labor hours (DLH), typically 30% of the total project cost. It is from this base that the allowable overhead, G&A, and fee are computed by preset ratios. The category of other direct costs (ODC), typically 15% of the total project costs, is a secondary denominator for costs actually incurred in a project. In fact,

Table 2 Comparison of labor hours percentages[a]

Major element	Mariner '64	Surveyor	Lunar Orbiter	Mariner '69	Mariner '71	Pioneer F/G	Viking Lander	Viking Orbiter	Average
Prog. mgt.	4.7%	7.3%	3.3%	4.4%	4.1%	5.3%	8.7%	5.0%	5.4%
Sys. anal/sys.eng.	1.5	9.2	3.1	3.2	2.2	0.5	8.4	6.5	4.3
Test	6.0	11.7	8.4	2.5	6.4	6.1	10.1	6.6	7.2
Qlty.assur/rel.	4.2	7.3	1.7	3.9	5.1	9.6	6.7	4.2	5.3
Assembly/integ.	1.9	2.8	5.2	3.1	1.3	2.2	3.2	2.6	2.8
Ground equip.	11.8	8.3	11.4	12.9	9.3	2.8	4.4	4.0	8.1
Launch/flt.ops.	12.3	9.8	8.6	4.1	9.2	17.5	5.8	12.7	10.0
Subtotal	42.4%	56.4%	41.7%	34.1%	37.6%	44.0%	47.3%	41.6%	43.1%
Structure	10.0	10.6	2.2	14.2	7.3	11.6	5.4	10.6	9.0
Propulsion	1.6	4.8	2.8	2.3	7.3	5.0	5.2	5.7	4.5
Guid/control	11.1	8.1	8.6	8.6	11.1	3.8	12.7	9.0	9.1
Communication	18.4	6.7	11.0	22.3	16.2	13.6	9.1	20.5	14.7
Power	6.9	3.0	3.6	6.4	4.8	6.2	2.2	4.1	4.7
Science	9.6	6.8	26.4	12.1	14.9	15.8	18.1	8.6	14.0
Misc	...	3.6	3.7	...	...	...	...	...	0.9
Subtotal	57.6%	43.6%	58.3%	65.9%	62.4%	56.0%	52.7%	58.4%	56.9%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

[a] W/O Fee.

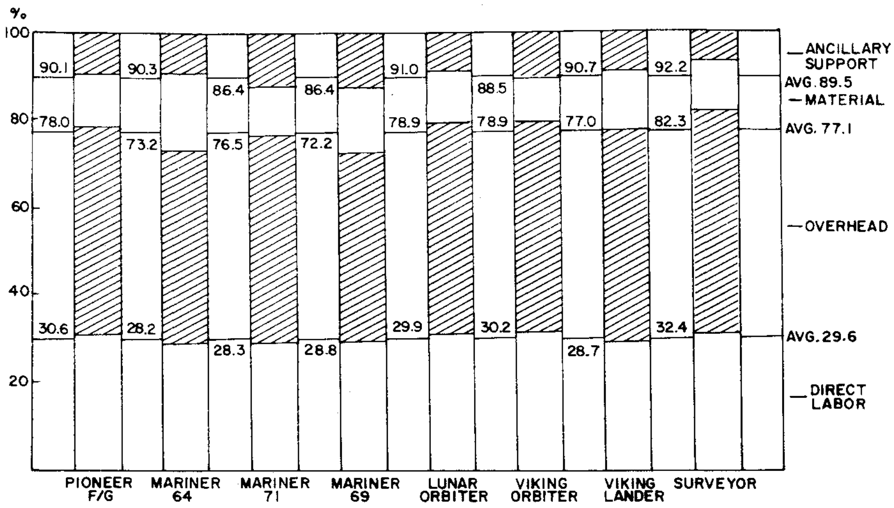

Fig. 3 Projects cost distribution (%).

Table 3 Labor as percent of total cost

	Hardware						
	Structure	Propulsion	G/C	Comm.	Power	Science	Act. proj. avg.
Mariner '64	24.0	27.3	29.7	30.0	29.0	29.0	28.3
Surveyor	34.4	26.9	29.9	32.0	32.5	31.7	31.3
Lunar Orbiter	36.9	28.4	27.7	26.5	28.2	26.2	27.1
Mariner '69	30.4	32.1	25.3	31.8	29.8	28.7	29.8
Mariner '71	31.3	21.1	28.9	31.6	30.0	26.7	27.9
Pioneer F/G	33.1	29.7	27.7	29.6	30.9	26.0	28.9
Viking Lander	27.6	28.1	28.4	19.7	27.8	25.7	25.4
Viking Orbiter	30.4	21.5	31.0	31.8	30.3	27.5	29.2
% Avg.	31.0	26.9	28.6	29.1	29.8	27.7	28.5

	Nonhardware							
	Prog.mgt.	S.A.	Test	Q.A.&R.	A.&I.	Grnd.eq.	L/F ops.	Act. proj. avg.
Mariner '64	24.1	36.3	27.6	26.3	27.9	28.0	30.0	28.0
Surveyor	34.6	35.9	33.6	37.7	32.7	30.0	31.5	33.5
Lunar Orbiter	35.6	42.5	39.3	40.6	38.0	25.8	32.2	33.3
Mariner '69	36.5	31.7	14.0	31.7	31.9	25.0	28.4	27.3
Mariner '71	39.0	30.9	30.8	28.5	40.4	23.0	29.5	28.9
Pioneer F/G	36.0	18.2	30.5	34.9	35.9	21.3	35.0	33.0
Viking Lander	29.1	41.6	31.9	37.1	23.4	26.4	42.4	33.4
Viking Orbiter	36.5	33.1	30.9	31.7	33.0	24.1	31.8	31.5
% Avg.	33.9	33.7	29.8	33.6	32.9	25.5	32.6	31.1

DLH & ODC are the only two categories by which a contractor can claim payment for his work on a project. Because direct labor hours, with ODC's, are the only parameters used to express the investment of time and materials in the spacecraft, and because they are so uniformly reported, they should be directly related to the overall cost of the project.

Not only should DLH's be used as a common denominator of spacecraft costs, but cost distribution between DLH's and ODC's should be an indicator of the mode in which the spacecraft is being built. A DLH investment of about 3 times ODC should indicate a developmental project with a high manpower investment, typical of the aerospace industry, while a much lower ratio should indicate a standardized procedure using bought-in components rather than hand made ones, typical of the automobile industry. It is anticipated that the Shuttle era will provide the impetus for the aerospace industry to move towards standardized production of spacecraft. And since lower cost will be incurred for direct labor hours, so also will the overhead cost be less and the total project cost reduced.

Total manhour effort for each of the eight projects studied is illustrated in Fig. 2. The levels of effort are quite different varying from 3.5-28.2 million direct labor hours. This variation is underscored when one considers that these projects encompassed over 10 years of NASA funding with varying designs and accomplishments. The percentage distrubition of labor hours across the 13 major categories is shown in Table 2. Scanning the table horizontally demonstrates considerable variation in many cost categories; this would be expected since the projects are quite different in character. Nevertheless, when examined from an average project viewpoint, one notes that the communications and science categories account for a significant proportion of subsystem development effort while launch/flight operations is the largest contributor to technical support areas. Those categories requiring the least effort in a total project are generally propulsion, power, systems analysis, and assembly/integration. Also, on the average, the relative labor effort between support and sybsystem categories is split 43.1% and 56.9%. One indication of the validity of using direct labor as a measure of total cost is to compare Table 2 against a similar breakdown of cost distribution. Results of the analysis show a very high correlation between the two distributions across every category. The largest individual difference amounts to about 5%, while the average difference is only 0.4%.

Another strong indicator of labor/cost commensurability is

Table 4 Recurring labor per flight article as percent of nonrecurring labor

Projects	Structure	Propulsion	Guidance/Control	Communication	Power	Science
Mariner '64	11.5%	18.9%	15.1%	19.2%	15.8%	23.0%
Surveyor	9.3	15.0	11.0	16.4	13.0	20.0
Lunar Orbiter	9.7	13.9	11.0	18.0	15.0	11.9[a]
Mariner '69	9.9	14.5	17.8	20.2	16.3	23.4
Mariner '71	16.9	13.9	21.5	15.1	12.1	32.8
Pioneer F/G	10.9	11.5	10.3	20.9	18.9	23.5
Viking Lander	9.3	15.1	11.0	16.4	13.0	20.0
Viking Orbiter	9.9	15.2	13.3	18.1	16.5	23.4
Avg.	10.9%	14.8%	13.8%	18.0%	15.0%	23.7%
Std. deviation	0.9%	0.7%	2.1%	0.7%	0.8%	1.5%

[a] Omitted in calculation.

the direct labor percentage of total project cost. Figure 3 shows the breakdown between DLH, overhead, materials, and ancillary support for the eight projects studied. The DLH costs are essentially a constant percentage of total costs, even though the latter are widely distributed across the different projects. The average DLH percentage over all categories and projects is 29.6% with a standard deviation of only 0.5%. It is of interest also to compare the DLH cost percentages in each individual category as shown in Table 3. One obviously expects greater variation in such a breakdown; however, the data generally confirms the pattern of about 30% of total cost attributed to direct labor. The few major exceptions can usually be explained in terms of accounting code changes in mid-project and bookkeeping anomalies.

Forecasting manhours has several distinct advantages over directly forecasting total project dollars; among these, separation of estimates from inflation factors and an ease in costing low-volume production. Inflationary factors are difficult to formulate for total project costs and often fail to accurately represent actual financial conditions within the industry. The space industry has not yet been able to use mass production techniques and thus the total cost of each completed item is not substantially decreased through additional production. Hence, project hardware cost is directly related to the manhours involved in development, fabrication, and testing. The present average direct labor ratio of 29.6% will likely change with the Shuttle Era. Manpower analysis during the coming period will highlight how cost has been affected since manpower is a homogeneous and standard unit across all projects. This approach provides management with a tool to evaluate the cost of new projects in light of established manpower-complexity relationships. Also, the effect of learning and inheritance can be analyzed and measured easier in terms of manpower requirements.

Nonrecurring vs Recurring Labor

The division between nonrecurring and recurring direct labor is not uniquely definable. However, the analysis has identified the completion data of the Proof Test Model (PTM) to be the best demarcation point for this division of labor. The PTM is a clearly defined point in a project, particularly from an historical standpoint. It is at least plausible that about as much recurring cost is incurred before the PTM as nonrecurring cost after the PTM, since work on the first flight article begins near the time of PTM acceptance. For the purpose of modeling, the PTM represents a very good project milestone marking the transition from nonrecurring to recurring manpower.

Yearly manpower records for each spacecraft subsystem were examined and compiled up to the PTM data with resultant split of NRDLH and RDLH. In the case of low production, it is reasonable to assume that recurring labor (RDLH) is equally divided among each flight article. The results of this calculation are shown in Table 4, which lists the percentage ratio of RDLH/NRDLH per flight article.

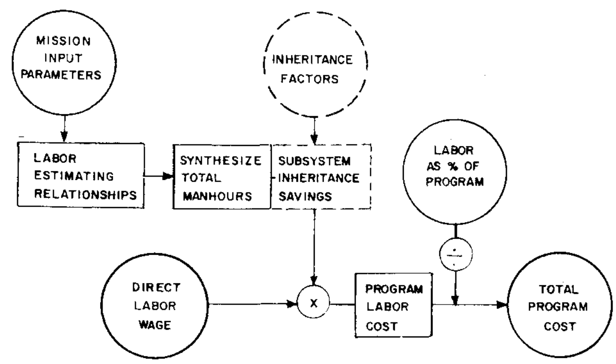

Fig. 4 Cost model schematic.

Although the ratios vary between different subsystems as would be expected, there is a fairly high degree of consistency in any given subsystem across all eight projects. For example, the average recurring labor in the propulsion subsystem per flight article is 14.8% of the nonrecurring design/development effort with a standard deviation of 0.7%. The average ratios listed here are subsequently used in the modeling procedure to calculate RDLH after the estimate of NRDLH is obtained.

Conversion of Manhours to Dollars

The two parameters needed to convert direct labor hours into total project cost are the wage rate ($/hr) and the percentage of project dollars invested in labor. The latter parameter has been discussed in the preceding paragraphs. For estimation purposes, wage rate can be chosen arbitrarily to represent a current fiscal year reference or to properly account for inflation over time. Alternatively, wage rate can be modeled on the basis of historical data and the model can be used for extrapolation purposes within careful limitations.

In pursuing the modeling approach, it was found that by taking the fiscal year date at which funding reached the 50% level one could obtain an accurate conversion of manhours to actual dollar expenditure. A regression analysis applied to all eight projects resulted in the following equation for average rate across all project categories. Wage Rate ($/hr) = 4.67 $(1.0513)^{(MY-1964.5)}$ where MY is the median fiscal date for a given project. This expression represents an average 5.13%/year inflation rate over the last decade which is also typical of the general economy. The accuracy of fit is measured by the standard error of only 19¢/hr.

In addition to the obvious time variation, wages also vary across project categories because of the different level of personnel employed. Technical support categories (e.g., program management) exhibit higher wage rates than most spacecraft subsystem categories with science being the major exception. Wage rate equations were derived for each of the thirteen project categories. It should be noted however, that is one is interested principally in estimating the total project cost, there

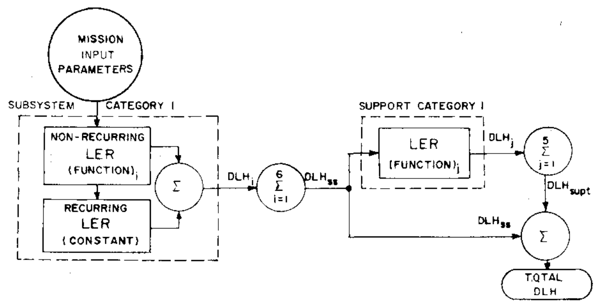

Fig. 5 Modeling approach for direct labor hours.

Table 5 Summary of modeling results for all subsystem categories

Project	Actual DLH total (000 hr)	Estimated DLH total (000 hr)	% Error
M64	2659	2737	2.9
M69	4338	3565	−17.8
M71	3309	3924	18.6
PIO	1976	2034	2.9
VO	5774	5532	−4.2
LO	4976	5004	0.6
VL	8733	8630	−1.2
SUR	11269	8294	−26.4

Mean error = −3.1%
Mean absolute error = 9.3%

is virtually no difference in the final result whether one applies the average wage rate or the individual category wage rates.

Cost Model Development

The manpower/financial analysis provided the basis for constructing a viable estimation model using the data base of the eight projects studied. The principal application of the model is to forecast cost of future automated planetary/lunar missions at the time of (pre) Phase A definition. A reasonable objective has been to obtain an average estimation error within 10% for projects included in the model data base, and an estimation error within 20% for future mission forecasting. Development of labor estimating relationships (LER's) would comprise the foundation of the model. Figure 4 is a flow diagram illustrating the key elements of the manpower/cost model.

Several requirements have been identified at the outset of model development: 1) Input parameters should be consistent with (pre) Phase A definition of subsystems and mission operations, e.g., weight, power, event times, etc. 2) Functional form of LER's should be simple algebraic expressions, e.g., linear, power law,exponential. 3) The number of coefficients in a given LER should be limited to improve statistical significance of data fit. 4) The LER should derive from an unbiased regression analysis; i.e., the balancing of plus and minus errors to yield a near-zero mean error.

In addition, two basic premises always should be kept in mind by the cost analyst or the user of the estimation model: a) A cost model does not represent "truth" but only a simplified, empirical approximation to actual cause and effect; and b) as a result of the phenomena of averaging, total project cost will be more accurately estimated than individual elements when viewed from a statistical standpoint of percentage error. A corollary to the averaging premise is, of course, that reduction of variance of fit in individual elements will further reduce error variance in total cost.

The procedure adopted for modeling direct labor hours is described by the schematic flow diagram in Fig. 5. Nonrecurring labor in each subsystem category is modeled as an appropriate function of the input parameters, while the

Table 6 Summary of modeling results for all support categories; direct labor in thousands of man-hours

Project	Actual DLH total	Model[a] DLH total	% Errors	Estimated[b] DLH total	% errors
M64	1956	2033	3.9	2074	6.0
M69	2247	2714	20.8	2213	−1.5
M71	1989	1981	−0.4	2334	17.3
PIO	1556	1370	−12.0	1391	−10.6
VO	4108	3642	−11.3	3414	−16.9
LO	3534	3420	−3.2	3444	−2.5
VL	7829	7846	0.2	7646	−2.3
SUR	15951	16166	1.3	7914	−50.4

Mean error = −0.1% = −7.6%
Mean absolute error = 6.6% = 13.4%

[a] Value based on actual total direct labor hours of subsystem categories.
[b] Value based on estimated total direct labor hours of subsystem categories.

recurring labor is taken to be proportional to the number of flight articles and the average recurring/nonrecurring ratio in that category. Each technical support category is modeled as a function of the total subsystem manhour expenditure. The diagram as drawn more clearly represents the estimation rather than the modeling procedure. In particular, the coefficients of the support category LER's are determined by least-squares fitting of the *actual* values of DLH_{ss} comprising the 8-project data base rather than the estimated values.

Space limitations do not permit a detailed listing here of all the labor estimating relationships which are given in the study documentation;[9] however, some general description is in order for purposes of this article. The spacecraft/mission input parameters total 21 in number and, for the most part, are weights of key subsystem elements. Nonwithstanding the desire to model on the basis of performance parameters, weight has been a meaningful composite parameter that correlates fairly well with design/development complexity and effort. In this sense, the present approach is not unlike earlier cost estimation models. Regardless the question of statistical significance, the ratio of total data points to the total number of model coefficients is approximately 3:1. By analogy this is akin to fitting a straight line (or power function) through 6 data points.

Modeling Results

The manpower modeling results for the total of all subsystem categories are summarized in Table 5. On a statistical basis across the eight projects, the model is slightly biased towards underestimation and the mean abolute error is 9.3%. The largest error is about 26% although 5 of the 8 projects are estimated to within 5%.

Table 6 summarizes the results obtained for the total of all technical support categories. It is necessary to make the distinction between modeled and estimated values of DLH since the support model coefficients derive from the assumption of perfect estimation of subsystem categories. Thus, the basic validity of the approach is indicated by the model errors, all of which are within desirable bounds. Average statistics over all projects show as essentially unbiased model (zero mean error) and a mean absolute error of 6.6%. The last two columns of Table 6 summarize the true estimation results computed on the basis of imperfect modeling of subsystem categories. In this case there is a tendency toward underestimation, but the mean absolute error of 13.4% is considered to be an acceptable result. The nature of the support category LER's is such that a compounding effect takes place when subsystem estimates are in error. This is particularly evident for the Surveyor project where the 26% underestimation of subsystem categories compounds to a 50% underestimation of support categories.

Table 7 Summary error analysis of total project cost model

Project	Actual ($M)	Estimated	% Error
Mariner 64	78.6	75.9	−3.4
Mariner 69	126.3	110.8	−12.3
Mariner 71	122.4	135.9	11.0
Pioneer F/G[a]	83.8	80.6	−3.8
Viking Orbiter	244.3	227.0	−7.1
Lunar Orbiter	139.2	145.0	4.2
Viking Lander[a]	416.2	403.1	−3.1
Surveyor	420.4	272.7	−35.1
Pioneer A-E	58.7	55.8	−4.9
ATS (A-E)	137.3	133.1	−3.1
MVM-73	98.0	93.5	−4.6

[a] RTS's included and project runout costs as of Aug. 1973.

Total project direct labor hours are obtained by adding the estimated values of Tables 5 and 6. When compared to the actual total DLH it is found that the largest error is 40% but that 7 of the 8 projects are estimated to within 18%. Total manpower estimates are converted to total cost estimates as described previously with the resulting comparison shown in Table 7. It should be noted that the project data base modeled does not include contractor fee, NASA Headquarters and Center management cost, or launch vehicle cost. This may explain any reconciliation between the "actual" costs listed and the reader's recognition of slightly different numbers. Table 7 indicates quite acceptable performance for the present manpower/cost model. The initial goal of 10% average error has been met. Out of the 8 projects, 4 are estimated within 5% while 7 projects are estimated within 12%. Since Surveyor represented the most complex unmanned space project undertaken in the early 1960's, and derived essentially zero inheritance from pervious experience, it is not too surprising that the present model underestimates its cost by 35%.

The cost model has also been applied to several other projects not included in the modeling data base. Historical projects such as Pioneer (A-E) and ATS /A-E) were selected as examples which were thought to represent a significant extrapolation test of the model. Results shown in Table 7 are encouraging in that model estimates are within 5% of actual project costs. Mariner Venus/Mercury was estimated on the basis of inheritance factors which are not included in the model and discussed in the last section. Without inheritance, MVM-73 is significantly overestimated at about $120M.

A final result of interest is the distribution of cost element errors itemized by project and category. Figure 6 summarizes this data in the form of a statistical histogram. The density function has a fairly sharp spike centered around zero error but the tailoff is less rapid than would be desired. Estimation errors associated with Surveyor are mainly responsible for the long tailoff and the negative bias in the distribution. The mean error and mean absolute error taken over the other 7 projects are, respectively, $0.4 and $2.3 million.

Uncertainty in Cost Estimation

In the introductory remarks several factors leading to inaccurate cost estimates were mentioned. It is appropriate now to re-examine this question. For a cost estimation procedure based on historical data sources, the question of errors may be considered in two parts, error attributed to the model itself and error introduced by uncertainty in input parameter values when applying the model. Factors contributing to model error include inadequate or unreliable cost data, imperfect relationships between cost and cost-driving parameters that describe the spacecraft and mission, and model structure deficiencies resulting in unaccountable factors in influence. By virtue of the detailed data collection and financial analysis methods employed in this study, the authors feel that error introduced by inadequate data sources has been minimized.

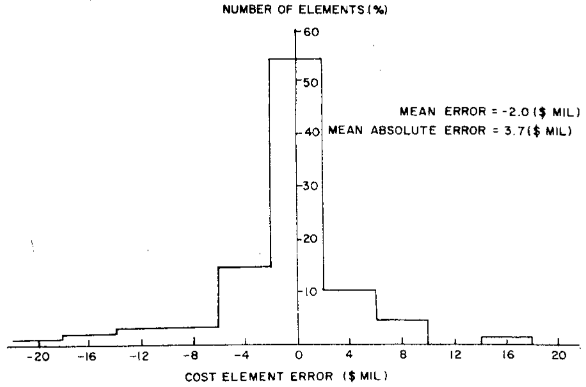

Fig. 6 Distribution of estimation errors for 88 cost elements (11 categories × 8 projects).

Mathematical relationship errors will exist in any estimation procedure which attempts (the necessary) simplification of actual cause and effect by empirical approximation. It is important, however, to re-examine these relationships from time to time and revise them as necessary. Model structure deficiencies must also be corrected as the cost model evolves in a changing environment; the question is addressed further in the last section of this paper.

The second major class of error, uncertainty, may be defined as lack of knowledge of the specific values of input parameters such as component and subsystem weights. Since the cost model described here is intended mainly for use at the pre-Phase A or Phase A timepoint of mission definition, the analyst must recognize that such uncertainty exists and will affect estimation accuracy. It was stated earlier that a reasonable goal for future mission forecasting is an estimation error within 20%. While it is expected that many of the input parameter values do not change more than 20% between early and final spacecraft configurations, a detailed analysis of this question has not been made. It would be worthwhile to do so in the future. In any event, the authors believe that uncertainty analysis should be introduced into cost estimation, so that a statistical distribution of project cost estimate is obtained rather than just the single value thought to be most likely. This can be done within the context of the present model by parametric analysis. Of course, it is understood that additional information is required of the spacecraft/mission design team in the form of uncertainty profiles associated with each model input parameter.

Extensions of the Method

Any cost model should be a dynamic entity reflecting new data sources and cost estimation procedures. The model described in this paper is continuing to evolve along the following lines:[9] 1) new data collection and analysis; 2) revision of launch/flight operations and ground equipment categories; 3) inclusion of science data analysis category; 4) application to atmospheric probe missions; 5) inheritance factors; and 6) low-cost payload concepts. The last two items warrant further discussion.

The effect of design/development and hardware inheritance can be important in estimating future space project costs. Mariner 71 is known to have derived such inheritance from earlier Mariner spacecraft, and that fact was apparent in the overestimation of several subsystem categories. Also, the design-to-cost ceiling approach applied to the Mariner Venus/Mercury project can be related in effect to inheritance factors. The cost estimating model has been extended to include four classes of inheritance affecting nonrecurring cost of subsystem development: a) off-the-shelf purchase; b) exact repeat; c) minor design modifications; and d) major design modifications. Typical cost saving values in these classes are 100%, 80%, 25% and 5%, respectively, and are applied to that fraction of a given subsystem which derives such inheritance. Further analysis of historical data from an inheritance viewpoint should result in an improved methodology and increased confidence when applying the cost model to future programs. Along these lines, it is noted that the concept of *negative inheritance* may be useful when attempting to estimate the cost of a future program expected to have significant new technology requirements for which the cost implication is not fully understood at the pre-Phase A level.

Perhaps the most important extension of the model lies in the area of estimating low-cost modularized payload concepts. Recent work by Lockheed in geocentric mission payloads and by JPL in planetary mission payloads can be useful in this regard.[10] Nondimensional sybsystem cost factors have been formulated through detailed analysis of several driver missions. These factors relate the low-cost payload estimate to baseline (historical) payload cost, and permit some degree of extrapolation in the analysis of other similar missions. We would propose to use the manpower/cost model described in this paper to derive baseline cost estimates, and then, with application of the special cost factors, obtain revised estimates for the new lost-cost designs. It is vital that NASA, in embarking upon a new course of payload design, utilize all the available experince of cost estimation to verify that they are in fact about to introduce a significantly lower cost concept. The insight given by the present analysis should prove to be a useful yardstick against which to measure future project costs.

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