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ESTIMATING AND CONTROLLING THE COST OF EXTENDING TECHNOLOGY: A REVISION AND EXTENSION

O. Douglas Moses

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

RADM. R. C. Austin
Superintendent

Harrison Shull
Provost

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This study tests hypotheses concerning the relationship between extensions in technology and costs, and provides approaches for estimating and controlling costs. The study begins by quantifying the incremental technological progress represented by a particular development project. Second, relationships between technology measures and development time and development costs are formulated and tested. Third, variance measures related to development cost are specified. Fourth, relationships between the development phase of a program and subsequent production costs are examined. The workability of the approach for cost prediction and control is tested and demonstrated by using technological and cost data from 18 satellite programs.

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ESTIMATING AND CONTROLLING THE COST OF EXTENDING TECHNOLOGY

O. Douglas Moses
Assistant Professor
Department of Administrative Sciences
Naval Postgraduate School
(408) 646-3218

PREFACE

This Technical Report is a revision and extension to a report previously conducted by Willis R. Greer: A Method for Estimating and Controlling the Cost of Extending Technology (Naval Postgraduate School Technical Report, NPS-54-88-002, Monterey, CA, March 1988). Dr. Greer's task was to develop a method for measuring extensions in the state of the art of technology in complex high technology systems and document relationships between technology extensions and cost. His report consisted of the following steps:

1. Review of literature on costing technology extensions.
2. a. Collection of data for 18 satellite systems measuring 17 distinct technology related characteristics for each system.

   b. Statistical "reduction" of the 17 measures of technology characteristics into four basic dimensions of technology. Factor analysis was used and four factors scores, representing the four technology dimensions, resulted.
3. Creation of measures of technological extension of new systems vis-a-vis predecessor systems. An "ellipsoid" approach relying on the euclidean distance between factor scores in 4-dimensional space was used.
4. Description of relationships between the development cost of systems and the technological extension required in creating the system.
5. Creation of measures of variances reflecting the difference between expected development cost, given the technological extension required, and actual development cost.

Further analysis indicates that the procedures used in creating measures of technological extension (step 3) were inconsistent with the way the basic dimensions of technology were measured (step 2b). More specifically, the ellipsoid approach used in step 3 requires as its input dimensions that have a "natural zero" point, where zero implies zero technological sophistication or complexity. The factor scores created in step 2b do not possess this property.

It should be noted that Dr. Greer's ellipsoid analysis creates and describes a novel approach to measuring technology extension, one that is potentially very useful in situations where the data fulfills the necessary constraints for its use. However, applying his approach when the input data are factor scores requires an arbitrary transformation of the factor scores which can only be justified on ad hoc basis.

This technical report first undertakes an analysis analogous to Dr. Greer's but uses an alternative approach to measuring technology extensions (step 3). The analysis continues to address the question of relationships between technology and development cost (step 4) and creates measures of development cost variances (step 5).

Additionally, this technical report extends the analysis to examine the production cost of systems. Relationships between measures of technology extension and development cost with subsequent production cost are documented. And models for estimating production cost are presented.

This technical report is self-contained, in that it can be understood without reference to Dr. Greer's previous analysis.

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ABSTRACT

When firms undertake new development projects, there is considerable uncertainty as to the amount of cost that will eventually be incurred. This study tests hypotheses concerning the relationships between extensions in technology and costs, and provides approaches for estimating and controlling costs. The study begins by examining the techniques currently available for measuring the state-of-the-art of technology. Next, methods for quantifying the incremental progress represented by a particular project are reviewed and extended. Third, relationships between technology measures and development time and development costs are formulated and tested. Fourth, variance measures related to development cost are specified. Fifth, relationships between the scope of the development phase of a program and subsequent production costs are examined. Finally, the idea of a development cost "premium," used to relate development costs to production costs, is introduced and tested. The workability of the approach for cost prediction and control is tested and demonstrated by using technological and cost data from 18 satellite programs.

ESTIMATING AND CONTROLLING THE COST OF EXTENDING TECHNOLOGY

When firms engage in research and development activities they encounter exceptionally difficult cost control problems. In fact, when such endeavors are undertaken on behalf of an external sponsor, a Department of Defense activity for example, the uncertainty involved generally requires using some variant of cost-plus pricing. If the task is performed speculatively, or on a fixed price basis, there is serious cost risk.

Part of the problem stems from an absence of clear measures of technology--how "advanced" is a particular aircraft or computer? Or how much more advanced is the objective of this particular development project? Additionally, there is no reliable methodology for associating development costs with different degrees of technological advance.

This study examines and extends techniques currently available for measuring the state-of-the-art (SOA) of technology and technology extensions by drawing on several suggestions from the literature. Relationships of SOA and SOA extension with development time and development cost are then specified and tested. The approach produces measures of variances that may be used in the process of controlling development cost. Relationships between development cost and production cost are also examined by introducing and testing a concept called the development cost "premium." The methodology developed is demonstrated and empirically tested with data from 18 satellite programs. The end result is the establishment of a series of relationships between technology and costs that can be used to estimate and control the cost of extending technology. We begin by reviewing approaches in the literature to measuring the technology embodied in a system.

MEASURING THE STATE OF THE ART OF TECHNOLOGY

The literature on technology measurement offers three broad approaches to determining the state-of-the-art (SOA) of technology for a given set of related systems. Each approach requires the knowledge of a number (n) of technology variables reflecting distinct properties or characteristics. Each combines the variables into a single SOA measure. For background, we review each approach, discussing advantages and disadvantages, and conclude that one approach is most applicable to our data.

Judgmental Weighting. This approach, discussed by Gordon and Munson [1981], expresses SOA as a direct combination of values of the technology characteristics. Gordon and Munson suggest two general forms of SOA equations.

$$SOA = K_1V_1 + K_2V_2 + . . . + K_nV_n \qquad (1)$$

and

$$SOA = V_1 \ [K_2V_2 + K_3V_3 + . . . K_nV_n] \qquad (2)$$

where

K_i = judgmentally assigned weights

V_i = the value of the ith technology-describing variable.

The first version of the model is a simple linear combination of weighted characteristics, the second version is a multiplicative form intended for use when one variable (V_1) must be present in the system. Gordon and Munson provide applications of the first version to measure the SOA for computer systems and the second version to measure the SOA for antibiotic drugs. Similar approached have been used by the Department of Defense to measure aircraft performance [Timperlake, et al., 1980].

While useful in some situations the approach has drawbacks. It is inherently subjective when the weights are assigned judgmentally, requiring a panel of experts. It also presupposes sufficient theoretical understanding of how individual characteristics "combine" to produce SOA in order to specify ex ante an appropriate form of the model. In addition, setting weights becomes quite difficult when n is large. Gordon and Munson suggest that factor analysis may be useful to reduce the number of technology descriptors, but the difficulty of ascribing intuitive meaning to factors increases the judgmental problem of assigning weights when factors are used as the technology descriptors.

Ellipsoid fitting. In 1985, Dodson [1985] reported an important advance in technology measurement which was based on work he did much earlier with Graver [1969]. The approach was to make use of convex (ellipsoidal) hypersurfaces to represent particular levels of technology. In order to utilize the approach, n technology attributes are specified and measured across a sample of the systems under study. An n-dimensional ellipsoid is then fit to the design attribute measurements. The curve follows the general form of an ellipse,

$$\frac{X_1^2}{a_1^2} + \frac{X_2^2}{a_2^2} + \cdot \cdot \cdot + \frac{X_n^2}{a_n^2} = 1 \qquad (3)$$

where

X_i = technology-describing variables

a_i = weights assigned by the ellipsoid fitting procedure.

The fitting technique uses a least squares algorithm, and operates on proportional distances of points from the origin.[1]

Once fit to a sample of systems, taken from a common time period, the ellipsoid surface can be viewed as reflecting the SOA of technology for that time period. The SOA of an individual system can be determined by plugging the values of the n technology-describing variables for the individual system into the ellipsoid equation to arrive at a measure of the radial distance from the origin for the system.

The method can best be illustrated in two dimensions, using data on aircraft systems from Martino [1985].[2] Figure 1 plots indices representing the speed and useful load of eight existing aircraft, and for one new aircraft (to be developed). Had the objective of the new aircraft development program been a point

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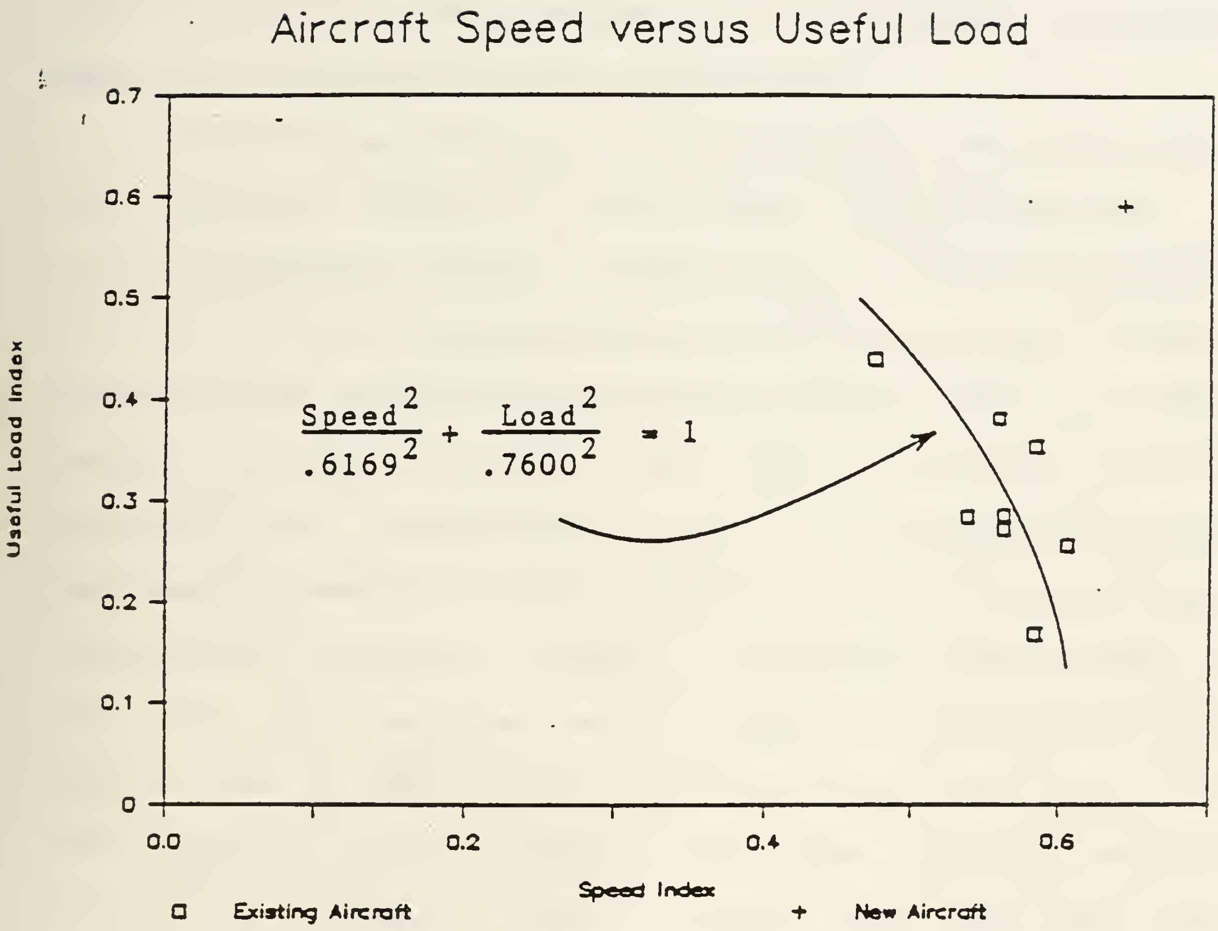
[1]Programs for fitting ellipsoids are available in Fortran and Basic in Dodson and Graver [1969] and Greer [1988], respectively.

[2]Martino also reported a third variable representing structural efficiency.

Figure 1

ELLIPSOID METHOD



near the existing technology surface (represented by the ellipsoid) only redesign effort would have been required--no advance in prevailing technology would be necessary. (Speed and useful load are attributes that designers can trade off against one another, subject to diminishing returns). But the new aircraft is required to be more advanced in both respects, so technology must be advanced beyond its current level.

One advantage of the ellipsoid approach lies in the fact that the resulting measure of technology, the proportional, radial distance from the origin, is scale-free. A second advantage lies in the theoretical appropriateness of the ellipsoid surface. It is consistent with the constraints designers face in trading off design attributes against each other to achieve an overall objective (e.g., speed versus load).[3] The disadvantages are that reasonable stability in the ellipsoid can be achieved only when the number of variables is small in relation to the sample size,[4] and that the n measures used to describe technology characteristics have to take on only positive values and have a natural zero point so that the distance from the origin is meaningful.[5] Thus, for example, factor scores resulting from variable

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[3]For elaboration of this last point see Knight's [1985] discussion and test of Grosch's law as it relates to design tradeoffs.

[4]The authors have found from experience that at least four observations per variable are needed.

[5]More formally, the measures need to be of ratio scale, rather than merely interval, ordinal or nominal scale. See Kerlinger [1973, Chapter 25]. Dodson [1970] discussed other constraints on appropriate measures to be used in the ellipsoid approach.

reduction techniques such as factor analysis can not be appropriately used to fit an ellipsoid.

"Year-of-Technology" Regression. A third approach frequently used [e.g. Alexander and Nelson, 1972; Dodson, 1977] employs multiple regression to combine several technology-describing variables across a sample of systems. The "year of technology" is the dependent variable, where this is usually interpreted as the year in which the system became operational.

$$Y = a + b_1X_1 + b_2X_2 + . . . + b_nX_n + e \qquad (4)$$

where Y = actual year the system became operational.

b_i = regression coefficients

X_i = technology-describing measures

e = residual

Predicted values (Y_e) from the regression equation for an individual system represents the "year-of-technology" or SOA for the system, i.e.,

$$SOA_j = Y_{ej} = a + b_1X_{1j} + . . . b_nX_{nj} \qquad (5)$$

As simplistic as this method seems, related work by Lienhard [1979] tends to support the concept. His paper studied the rate at which technology is improved, and how (whether) this rate changes through time. He studied several forms of technology (clocks, steam power, land transportation, low temperatures, air transportation) over extended time periods. The most relevant observations to come from Lienhard's study was that the rate of improvement of a particular technology, once established, does not change. If this is literally correct (and his data do seem to support the observation), there could be some major implications for the cost, and even the feasibility, of attempting to effect technological advances "before their time". If a desired advance could normally be expected to occur only by some quasi-naturally established date, attempts to accelerate this process would be very costly. Accordingly, the "year of technology" approach may be well reasoned.

MEASURING EXTENSIONS IN TECHNOLOGY

To address the issue of advances in technology, measures of increments in technology are necessary. In general, the procedure for measuring increments in technology is similar across the three approaches: A reference point, reflecting the current state of technology, is established and the distance between the reference point and the technology in a particular system is measured. Out data (to be discussed in a following section) describes technology characteristics using factor scores. Consequently we rejected the judgmental weighting approach (attaching weights to factors is conceptually difficult) and the ellipsoid approach (factor scores violate the ellipsoid assumptions) and relied on the year-of-technology approach.[6]

The essence of the year-of-technology approach is to combine numerous technology descriptions into a summary technology measure, expressed in terms of time (years). Using this notion,

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[6]Greer [1988] discusses procedures for creating measures of technology extension from the ellipsoid approach.

we create three technology measures for each individual system: REACH, ADVANCE and STAND.

Recall that the predicted value (Y_e) from the regression (Equation 5) represent the year-of-technology for a given system. Y_e is a summary measure of the degree of technology embodied in the system. We define Y_e as the technological REACH of the system.

Alexander and Nelson [1972] and Dodson [1977] argue that if the actual year (Y) a system was produced was less than the predicted year ($Y < Y_e$) then that system was "ahead of it's time": the "state-of-the-art" was advanced when that model was developed. (Conversely, if $Y > Y_e$ then the system was "behind the times.") Therefore, Y_e-Y measures the extent to which each system represented a technological advance. In short, we define ADVANCE as Y_e-Y

Finally, since the state of the art of technology at any moment is defined in terms of years, the year in which a system becomes operational represents where technology in general currently "stands." Hence STAND simply equals Y.

Our interest in these three technology measures is in using them to assist in cost prediction and control. This will be illustrated with a sample of satellite systems.

SAMPLE AND DATA

Our sample consisted of 18 satellite programs; with the initial satellite of each program first launched between 1966 and

1986. The sample included several types of satellites - communications, surveillance, navigation, etc. Data were obtained from the U. S. Air Force.[7]

All the methods of measuring the state-of-the-art of technology and technology extensions require basic data describing properties or characteristics of the systems under study. Data describing 84 technical characteristics of each of the 18 satellites were available.

Variable Selection

In selecting variables to be used in measuring the technology embedded in the category of systems to be studied, technical expertise must be sought. In selecting variables, the experts should bear in mind that the technology-describing characteristics must be at least partially alterable by engineering development decisions. They should choose characteristics which are goals of the design process. Ideally the variables should be specified so that increasing values correspond to greater technical difficulty. Finally, the values of the variables should be ascertainable during the early stages of the system's life-cycle so they may be used in the process of predicting costs.

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[7]These data were supplied by Headquarters, Space Division (AFSC), Los Angeles Air Force Station, Los Angeles, CA. While the data are not classified, the authors were asked not to identify specific satellites by name or designator. To honor this request the systems will be referred to only by randomly-assigned code letters. The authors are particularly indebted to Captain Blain Webber, USAF, for his assistance and cooperation.

Some of the 84 properties included in the data set could be considered design objectives, and therefore appropriate as technology indicators, but many others were simply byproducts of the design. Others were potentially useful, but were not stated in a form that revealed much about the technology embodied.

Our first step was to identify which of the 84 characteristics were relevant to describing the state of technology in the satellite systems. Technical expertise was sought and extensive data review, conversations and conferences took place among a small group of satellite experts.[8] The result of these conferences was consensus identification of 17 variables that are well-suited to describing satellite technology. The 17 variables are listed in Appendix I.

Second, with 17 variables to describe 18 systems, variable reduction was necessary. Principle components factor analysis with varimax orthogonal rotation was conducted.[9] The result was a final factor matrix explaining 81.7% of the variance in the technology variables. Four separate factors had eigenvalues greater than one. They were retained for use in the remainder of the analysis. The four factors reflect four different aspects of satellite technology which we labeled as follows:

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[8]The authors are indebted to the Naval Postgraduate School, and particularly to Dr. Allen E. Fuhs, Distinguished Professor of Aeronautics & Space, Dr. Richard W. Adler, Adjunct Professor, Elec. & Comp. Engineering, and Mr. Marty Mosier, Staff Engineer, Space Systems, for their invaluable assistance.

[9]For a comprehensive discussion of factor analysis see Harman [1976].

Factor 1: Mission requirements

Factor 2: Orbital

Factor 3: Electrical Power

Factor 4: Environment

A detailed description of the factor analysis is contained in Appendix II. Factor scores for each of the 18 satellites are contained in Table 1.

CREATING TECHNOLOGY MEASURES

Following the year-of-technology approach, the launch year (of the first unit) of each satellite program was regressed against the MISSION, ORBITAL, ELECTRICAL and ENVIRONMENT factor scores. Results are in Table 2. Note that the overall model is significant and explains a large portion of the variance (adjusted R^2 = .65). In addition, each factor is reasonably significant[10] with positive coefficients, consistent with increasing values of the four technology descriptors reflecting increasing technology over time. This provides some confirmation that the factor scores appropriately reflect dimensions of technology and technology growth.

Figure 2 shows a plot of year-of-launch (Y) versus year-of-technology (Y_e). Using the approach outlined earlier, we can determine values for STAND, REACH and ADVANCE for each system. By way of illustration we might view system H, highlighted in the Figure. It was actually launched in 1969 (STAND) but has a year-

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[10]Since our hypotheses are directional we use one tail tests of significance.

TABLE 1

Factor Scores

System	Fact 1	Fact 2	Fact 3	Fact 4
A	0.5481	1.4894	1.4514	1.3038
B	-0.7021	-0.6149	0.8253	-0.8771
C	1.4523	-1.1906	0.3233	2.3646
D	-0.2591	1.1941	0.8042	0.0857
E	-0.8919	-0.7342	0.4668	-0.6761
F	-0.5195	0.6648	-1.3337	0.8363
G	-0.2870	-1.3133	-1.7576	0.8937
H	0.4619	-0.8923	-0.4650	-1.1932
I	2.1776	-1.0966	0.4696	-0.3093
J	-1.4171	-1.0918	1.5999	-0.0233
K	-1.0725	0.9872	0.2058	0.4739
L	-0.9641	-0.6474	0.0670	-0.2184
M	-0.1629	-0.8299	0.2157	-0.4064
N	-1.1595	0.7442	-1.0434	1.0676
O	0.6814	0.9718	-0.4915	-1.6992
P	0.1755	0.7231	-0.4819	-0.8667
Q	0.7529	0.4861	-1.7235	-0.4232
R	1.1859	1.1505	0.8674	-0.3126

TABLE 2

YEAR-OF-TECHNOLOGY REGRESSION

Dependent Variable: Launch Year

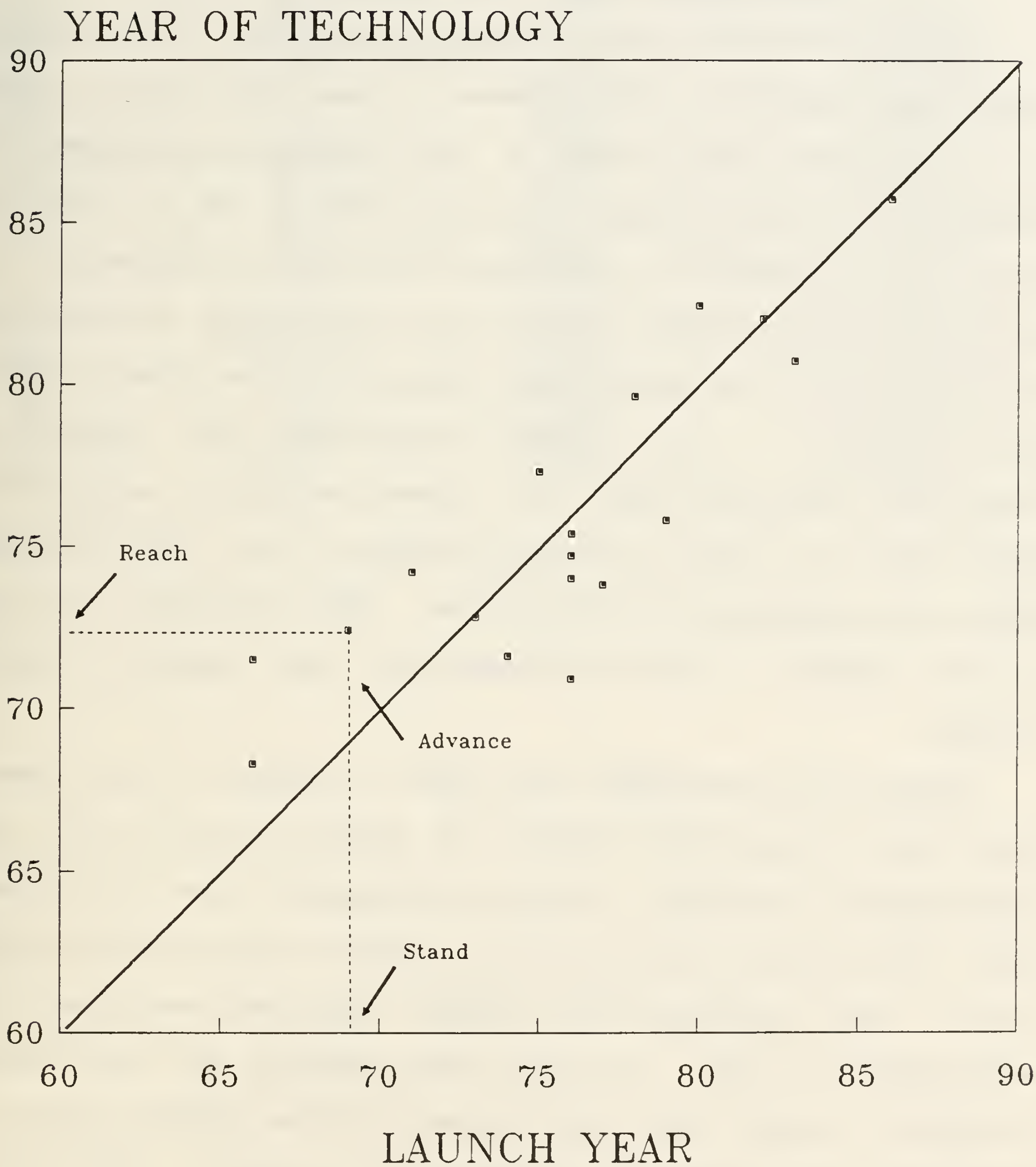
Independent Variables	Coefficients	t	Significance*
Intercept	75.720	-	-
MISSION	2.213	2.84	.007
ORBITAL	1.103	1.41	.090
ELECTRICAL	3.698	4.74	.001
ENVIRONMENT	1.349	1.73	.053

Model Statistics

F : 8.85
Significance: .0011
R^2 : .73
Adjusted R^2 : .65

*One Tailed Tests

FIGURE 2
YEAR OF TECHNOLOGY PLOT



of-technology value (REACH) that falls between 1972 and 1973. Thus it was three to four years ahead (ADVANCE) of the general trend in technology. More precise measures for system H and the other systems are in Table 3.

DEVELOPMENT COSTS - HYPOTHESIS AND TESTS

Our next objective was to explain development costs using the technology measures. Data relevant to this (and later) portions of the analysis are in Table 4. The reported development cost figures are "nonrecurring" costs provided by the Air Force for each system, adjusted to constant 1986 dollars (thousands). The development time figures report the time elapsed in months from the awarding of the development contract to the first launch of the satellite. The reported production cost figures are "recurring" costs per unit, i.e., costs incurred in manufacturing each unit of a given satellite program after the development phase, also adjusted to 1986 dollars. The production run figures are the number of units produced for each separate satellite program.

System A was excluded from Table 4 because it was known to have been a very minor upgrade of another satellite for which data were not available. Data on development time for systems D and F were unavailable because the contract dates were unknown. D and F were excluded from analyses requiring development time and production costs. The data were complete for the remaining 15 systems, except that only the year of the contract award, not the month, was known for systems R, C and I. The working

TABLE 3

TECHNOLOGY MEASURES

SYSTEM	STAND (YEAR OF LAUNCH)	ADVANCE	REACH (YEAR OF TECHNOLOGY)
A	86	-.30	85.70
B	76	-.64	75.36
C	82	.01	82.01
D	78	1.55	79.55
E	77	-3.25	73.75
F	66	5.50	71.50
G	66	2.34	68.34
H	69	3.43	72.43
I	83	-2.35	80.65
J	75	2.26	77.26
K	79	-3.16	75.84
L	73	-.17	72.83
M	76	-1.30	74.70
N	74	-2.44	71.56
O	71	3.19	74.19
P	76	-2.05	73.95
Q	76	-5.02	70.98
R	80	2.40	82.40

TABLE 4

DEVELOPMENT AND PRODUCTION DATA

SYSTEM	DEVELOPMENT COST	DEVELOPMENT TIME (months)	PRODUCTION COST	PRODUCTION RUN
A	-	-	-	-
B	91707	37	23483	4
C	157820	64	46865	2
D	50393	-	-	3
E	108085	37	54094	3
F	509262	-	-	5
G	279270	20	49847	23
H	73594	25	50414	1
I	451274	86	51972	6
J	155524	46	118752	1
K	14943	36	17697	1
L	37228	32	7715	3
M	319499	37	387034	1
N	32585	28	11266	3
O	116580	27	35666	4
P	121931	33	56574	3
Q	64384	37	28048	3
R	180653	56	39432	15

assumption adopted was to date the contract award at mid-year, but other assumptions were analyzed for result sensitivity with very little disparity.

Development Cost and Technological Complexity

Our first hypothesis was that there is a direct relationship between development cost and the scope of the development task at hand, measured in terms of technological complexity. Two variables capture complexity: STAND measures the current state of technology at the time of project development. As the state of technology increases, designers are operating at a greater level of complexity and consequently costs of extending technology are hypothesized to increase. ADVANCE measures the increment in technology to be achieved by the development project; costs are also hypothesized to increase with magnitude of the advance required. (REACH is simply the sum of STAND and ADVANCE; consequently it contains no additional information and is excluded from the analysis).

H_1: Development Cost = f (+ STAND, + ADVANCE)

To test the first hypothesis, a multiple regression was run. Results are in Table 5. Coefficients for both STAND and ADVANCE are positive as expected, but neither is significant at traditional levels. The model as a whole is unimpressive: The R^2 is low (.12) and the overall model insignificant.

The low explanatory ability of the model is not totally unexpected. Dodson [1977] also attempted to predict development costs (of computer systems) using technology variables, with

TABLE 5

REGRESSION OF DEVELOPMENT COST ON TECHNOLOGY MEASURES

Dependent Variable: Development Cost

Independent Variables	Coefficients	t	Significance*
Intercept	30937	-	-
STAND	1749	.19	.425
ADVANCE	18833	1.23	.120

Model Statistics

F : .95
Significance: .4120
R^2 : .12
Adjusted R^2 : -.01

*One Tailed Tests

little success. He concluded that his poor result was due to incomplete modeling.

Development Time and Technological Complexity

We hypothesize that there is an intervening variable between development cost and technological complexity: development time. Complexity affects time; time effects cost. Our second hypothesis then is that the difficulty of the development task, as measured by the time required for its completion, is a positive function of technological complexity.

H_2: Development Time = f (+ STAND, + ADVANCE)

Table 6 shows results of regressing development time on the technology variables. Results are considerably more impressive. The model is highly significant with an adjusted R^2 of .75. Both STAND and ADVANCE have significant positive coefficients as expected. The actual time required to complete a development project is a function of both the level of technological complexity at which the task is taking place and the increment in technology to be achieved.

Development Cost and Development Time

Development cost should be related to development time, but development cost may not be a smooth function of time. If a program drags on beyond its intended completion date, additional resources may be employed to accelerate its completion. Hence, it may be relatively more costly to compress the required accomplishment into an increasingly abbreviated time horizon. We

TABLE 6

TIME REGRESSION

Dependent Variable: Development Time (months)

Independent Variables	Coefficients	t	Significance*
Intercept	-239	-	-
STAND	3.70	6.55	.001
ADVANCE	2.03	2.07	.030

Model Statistics

F : 22.25
Significance: .0001
R^2 : .77
Adjusted R^2 : .75

*One Tailed Tests

took the predicted times from the above model as a "natural" development time, and the residuals as departures (which may or may not have been planned ex ante) from this natural time. We expect both time measures to be positively associated with cost, suggesting the following hypothesis:

H_3: Development Cost = f (+ Predicted Time, + Residual Time) where Residual Time = Actual Time - Predicted Time.

The results of the multiple regression (Table 7) are good, although not as strong as the previous test. Both time variables have reasonably significant positive coefficients as hypothesized, and as expected the coefficient for the residual time term is larger than that for predicted time. This is consistent with extension of a project beyond its natural development time leading to increased time pressure, increased resources expended to accelerate completion and increased costs. Additionally note that the explanatory ability of this model (adjusted R^2) has improved markedly relative to the first model which explained cost directly by the technology variables, indicating that development time is indeed an intervening variable in the determination of costs.

INTERPRETATION OF RESULTS FOR CONTROL

The most basic principle of cost control is to attribute differences between anticipated costs and actual costs to causes. That is, to explain variances. The preceding analysis affords an opportunity to do that. Consider the information contained in

TABLE 7

DEVELOPMENT COST REGRESSION

Dependent Variable: Development Cost

Independent Variables	Coefficients	t	Significance*
Intercept	52841	-	-
Predicted Time	2350	1.55	.074
Residual Time	10482	3.59	.002

Model Statistics

F : 7.64
Significance: .0073
R^2 : .56
Adjusted R^2 : .49

*One Tailed Tests

Table 8. The column labeled "Ex Ante Cost Estimate" was constructed in the following way:

1. The particular system's values for STAND and ADVANCE (both determinable ex ante) were entered in the "Time" regression to predict a time that would be required for the system's development.

2. To calculate the ex ante prediction of development cost, the Predicted Time was input to the "Cost" regression, with Residual set equal to zero (thereby assuming the predicted time would be achieved).

Next the actual time for the project was compared with the predicted time to determine the Residual (ex post). The Cost regression was then revisited with values for both variables, and a new cost estimate constructed, considering the actual time for the project. This produced the column titled "Cost Est Based on Act Time".

The difference between the ex ante cost estimate and the cost estimate based on the project's actual time has been termed the "Variance Due to Time". This figure is a best estimate of the portion of the total variance that can be attributed to the cost consequences of time delays (or to fortuitus and perhaps unforeseen acceleration of the schedule). Negative figures are favorable, positive are unfavorable.

When Actual Cost is compared with the cost estimate based on actual time the result is a "Cost Control Variance". Given that the project actually took t months to complete, the cost should

TABLE 8

DEVELOPMENT COST VARIANCE DATA

SYSTEM	EX ANTE COST ESTIMATE	VARIANCE DUE TO TIME	COST EST. BASED ON ACT. TIME	COST CONTROL VARIANCE	ACTUAL COST	TOTAL VARIANCE
B	150150	-46173	103977	-12270	91707	-58442
C	205478	-9927	195551	-37731	157820	-47658
E	146449	-29664	116784	-8699	108085	-38364
G	77307	100530	177837	101433	279270	201964
H	108593	13394	121987	-48393	73594	-34999
I	202957	231936	434894	16380	451274	248317
J	155288	25253	180541	-25017	155524	236
K	164271	-119643	44628	-29685	14943	-149328
L	126265	7948	134214	-96985	37228	-89037
M	147029	-32254	114775	204724	319499	172469
N	124175	-24658	99517	-66931	32585	-91590
O	124871	-38247	86624	29956	116580	-8291
P	143478	-58343	85134	36797	121931	-21546
Q	129307	46796	176103	-111718	64384	-64922
R	199461	-66948	132513	48140	180653	-18808

have been "Cost Est Based on Act Time". The actual cost was a different amount, so the variation is attributed to the contractor's success (or lack thereof) in cost control. Again, negative figures are favorable.

The variances have been shown graphically in Figure 3. The variances are expressed as a percentage of Ex Ante Cost.[11]

As Figure 3 indicates, there were non-trivial unfavorable total variances for three of the 15 programs(G, I, M). For program I the cause of the unfavorable variance appears to have been mostly attributable to a timing problem. For Program M the origin of the problem was cost control. Both cost control and timing problems appear to have been significant contributors to the total variance for program G; its total variance is by far the largest. (If these variances seem large compared with what the reader is accustomed to, consider the fact that there is far greater uncertainty surrounding a research project's costs than those of a routine manufacturing operation.)

Program J is interesting in that an unfavorable cost control variance is offset by successful control over time, leaving the total cost variance insignificantly small.

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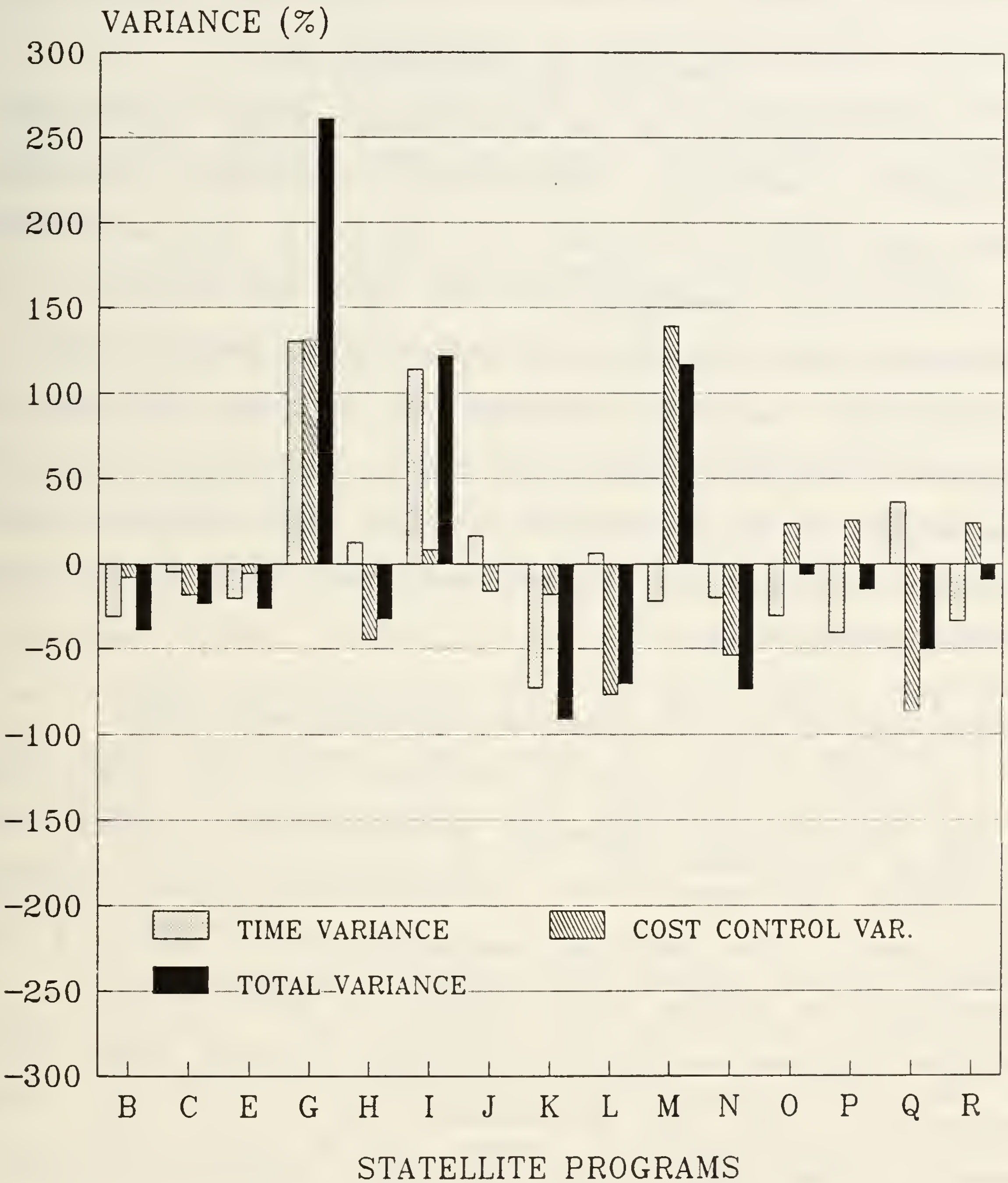
[11]The variances could also have been expressed as a percentage of Est. Cost Based on Actual Time or Actual Cost. Use of either of these alternatives would of course change the individual percentages, but not the sign of the variance nor the relative size of the time, cost control or total variance for an individual system.

FIGURE 3
DEVELOPMENT COST VARIANCES



The most significant favorable variances are for programs K, L and N. Successful cost control is the primary source of the favorable variance for L and N. Program K has the largest favorable variance and while both cost control and time control contribute, control over time is the primary explanation.

ANALYSIS OF PRODUCTION COST

With completion of the development phase, three kinds of information, reflecting technological complexity, development stage costs and cost variances, are available. Our next question was whether our measures resulting from the analysis of the development phase are useful in explaining production costs.

In the following sections we develop and test four hypotheses concerning the relationship of production cost with the "scale" of the development program, cost control during the development phase, the technological complexity of the system, and the production run.

Production Cost and the Scale of the Development Phase

To summarize the previous analysis: We first used measures of the technological complexity of the program (ADVANCE, STAND) to predict development time. We calculated Ex Ante Development Cost directly from predicted development time. (One is a linear transformation of the other; hence they both capture the same variance and are equivalent when used in linear models such as regression.) Ex Ante Development Cost is our best summary measure of the scale of the development program known prior to its start. We then analyzed the differences between Ex Ante and Actual Development Cost into variances. The Ex Ante Cost plus the variances equal the Actual Cost, which is our best summary measure of the scale of the development program known after its completion.

Our initial hypothesis is that production costs are positively related to the scale of the development program; simply put, systems that are costly to develop are costly to produce.

H_4: Production Cost = f (+ scale of the development project)

If the variances due to time or cost control are isolated to the development phase of a program and have no implications for production cost, then Ex Ante Development Cost should provide the best measure of the scale of the program to use in explaining production cost. Alternatively, if variances during the development phase indicate conditions that can be expected to recur during the production phase of the program, then the ex post Actual Development Cost should be a better measure of scale to explain production cost. Our intuition tells us that cost overruns during development are associated with higher cost during production.

It is necessary to control for another factor potentially affecting cost. The production cost measures are average unit costs determined by dividing the total production cost for a satellite program by the number of units produced (cost per specific individual unit were not available). It is well established that unit production cost typically decreases as the number of units produced increases, due to the learning curve effect. We control for this effect by explicitly testing the following:

H_5: Production Cost = f (- Production Run)

where the Production Run is the number of units produced for each satellite program.

Table 9 (Models 1 and 2) shows separate regressions of Production Cost on the two alternative development cost measures: Ex Ante and Actual Development Costs, respectively. Production Run is included in each model as a control and as a test of Hypothesis 5. The natural log of each of the variables is used in the regressions, for two reasons.

First, learning curve theory states that the decrease in production cost with increases in production quantity is log linear rather than linear. Hence logged variables are the theoretically appropriate measures when used in linear regression.[12]

Second, the regressions of production cost on development cost are considerably heteroscedatic, i.e., residuals are larger when cost is higher. This violates an assumption of regression that error variance is constant over all observations, resulting in residuals that are not of minimum variance. A common solution to this problem is to log the variables (see Neter and Wasserman,

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[12]For background on learning curve theory see Kaplan [1982, pp. 97-105] and Womer [1979].

TABLE 9

PRODUCTION COST REGRESSIONS

Dependent Variable: Production Costs (log)

MODEL 1

Independent Variables	Coefficient	t	Significance*
Intercept	7.219	-	-
ExAnte Dev. Cost(log)	.304	.29	.388
Production Run(log)	-.202	-.72	.244

Model Statistics

F : .35 — R^2 : .05

Significance : .7125 — Adj. R^2 : -.10

MODEL 2

Independent Variables	Coefficient	t	Significance*
Intercept	.041	-	-
Act. Dev. Cost(log)	.969	7.02	.0001
Production Run(log)	-.576	-4.31	.0005

Model Statistics

F : 26.17 — R^2 : .81

Significance : .0001 — Adj. R^2 : .78

MODEL 3

Independent Variables	Coefficient	t	Significance*
Intercept	6.72	-	-
ExAnte Dev. Cost(log)	.369	.65	.265
Time Variance	3.3×10^{-6}	1.79	.052
Cost Control Variance	9.7×10^{-6}	5.33	.001
Production Run (log)	-.455	-2.74	.010

Model Statistics

F: 8.20 — R^2: .77

Significance: .0034 — Adj. R^2: .67

* One Tailed Tests

1974). Hence logged variables are methodologically more appropriate.

Results in Table 9 show that Model 2 is clearly superior to Model 1 with respect to significance and explanatory power (adjusted R^2 of .78). Production cost is strongly associated with the scale of the development program, measured ex post. Further more, when development scale is "properly" measured ex post, production cost is also seen to be significantly dependent on the production run. Longer runs reduce per unit cost.

Comparing the results of the two models, the implicit inference from the poor explanatory ability of Ex Ante Development Cost is that variances incurred in the development phase of a program are "permanent" in that they contain information beyond that reflected in Ex Ante Development Cost relevant to explaining subsequent production costs. Stated as a hypothesis:

H_6: Production Cost, unexplained by ex ante development cost = f (+Dev. Time Variance, +Dev. Cost Control Variance)

We test this explicitly by additionally including the two development cost variances in Model 1 and re-running the regression. Results (Model 3, Table 9) show both the time variance and cost control variance incurred during development to be strongly associated with subsequent production cost.

Production Cost and Technological Complexity

Recall that Ex Ante Development Cost is a direct linear combination of two technology variables (ADVANCE and STAND) and that Ex Ante Development Cost had little ability to explain production cost. This might suggest that technology is unimportant in explaining production cost. Such a conclusion may be premature.

We know that development costs (ex post) are a good predictor of production costs; that the scale effect holds. But the degree to which development costs are associated with production costs may depend on the technological complexity of the system produced.

The outcome of a development project is the creation of the first unit or prototype of a particular system. The cost of that prototype system will include both "pure" development cost associated with extending technology and, additionally, the manufacturing costs (materials, labor, overhead) associated with construction. The pure development costs are non-recurring. The construction costs recur with the production of each additional unit after the prototype.[13] Let's construct a ratio, labeled the "development premium" ratio, to relate prototype costs (numerator) with the costs of additional units (denominator).

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[13] In fact that is how development and production costs are defined in this study, in terms of non-recurring and recurring costs.

$$\text{Development Premium Ratio} = \frac{\text{Development Cost} + \text{Production Cost}}{\text{Production Cost}}$$

Note this is just a way of relating development and production costs while controlling for scale.

Assume for a moment a "development" program that requires "zero" extension of technology or is of "zero" technological difficulty. In essence "pure" development cost should be zero and the cost of the prototype should equal the cost of producing any follow-on unit. The development premium ratio should equal 1; there should be no "premium" to extend technology by zero amount. Alternatively assume a development project with "great" technological complexity. The pure development costs should be large and should not recur for follow-on units; thus the development cost "premium" should be large (and the ratio greater than 1). If the size of the development cost premium is driven by the technological complexity of the task then the ratio should be predictable using a measure of the technological complexity of the system being developed and produced. REACH is a measure of the total technological complexity of the systems. Operationally our hypothesis is:

H_7: Development Premium = f (+ REACH)

Table 10 shows results of regressing the premium ratio on REACH. (Production Run is again included as a control. Production Run should have a positive sign in this regression since longer production runs imply smaller unit production cost, reducing the

TABLE 10

DEVELOPMENT COST PREMIUM REGRESSION

Dependent Variable: Development Premium Ratio

Independent Variables	Coefficients	t	Significance*
Intercept	-7.750	-	-
REACH	.135	1.42	.091
Production Run(log)	1.647	4.03	.001

Model Statistics

F: 9.01
Significance: .0041
R^2: .60
Adjusted R^2: .53

*One Tailed Tests

denominator proportionately more than the numerator, and thus increasing the ratio.) The coefficient for REACH is positive as expected and approaches traditional levels of significance. The implication is that the overall technological complexity of a system is useful in explaining the degree to which development cost may exceed production cost.[14] The adjusted R^2 of this regression is not as large as that found in Model 2, Table 9, but use of the ratio has already controlled for scale, so this regression explains only the additional variance not explainable by scale.

Production Cost Variance

The regression model in Table 10 provides an equation for estimating production costs which includes three variables (Actual Development Cost, Production Run, REACH).

$$\frac{\text{Dev. Cost + Prod. Cost}}{\text{Prod. Cost}} = a + b_1 \text{ REACH} + b_2 \text{ Prod. Run}$$

The equation captures a) the scale of the development phase (through the Development Cost measure), b) the effect of learning on production cost (through the Production Run measure) and c) the development cost premium idea (through REACH). REACH is known prior to development. Development Cost is known after

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[14] We ran a regression using STAND and ADVANCE in place of REACH. The coefficient for STAND was significant ($p = .094$) while that for ADVANCE was not. The adjusted R^2 of the regression was slightly lower (.50), suggesting that REACH alone is our best technology measure for capturing the relationship between development and production cost.

development but prior to production. The actual production run is known only following production, but is a variable a cost analyst can set prior to production in order to estimate unit costs at an anticipated production level.

By plugging in (known) values for the three variables and solving for production cost, we arrive at a predicted production cost. Subtracting from actual production cost provides a measure of production cost variance (positive values are unfavorable). While we do not have the ability to break the variance down into causes, the model does provide a benchmark for assessing if production cost is out of line, given the knowledge gained during the development phase.

Figure 4 plots the production cost variance as a percentage of the production cost. While some of the variances are not "small", overall they are considerably smaller than the development cost variances displayed previously in Figure 3. This is not surprising. Knowledge about costs gained from the development phase should allow for better estimation of costs during production.[15]

SUMMARY AND CONCLUSIONS

This study has examined relationships between extensions in technology and both development cost and production cost associated with achieving extensions. The result has been to

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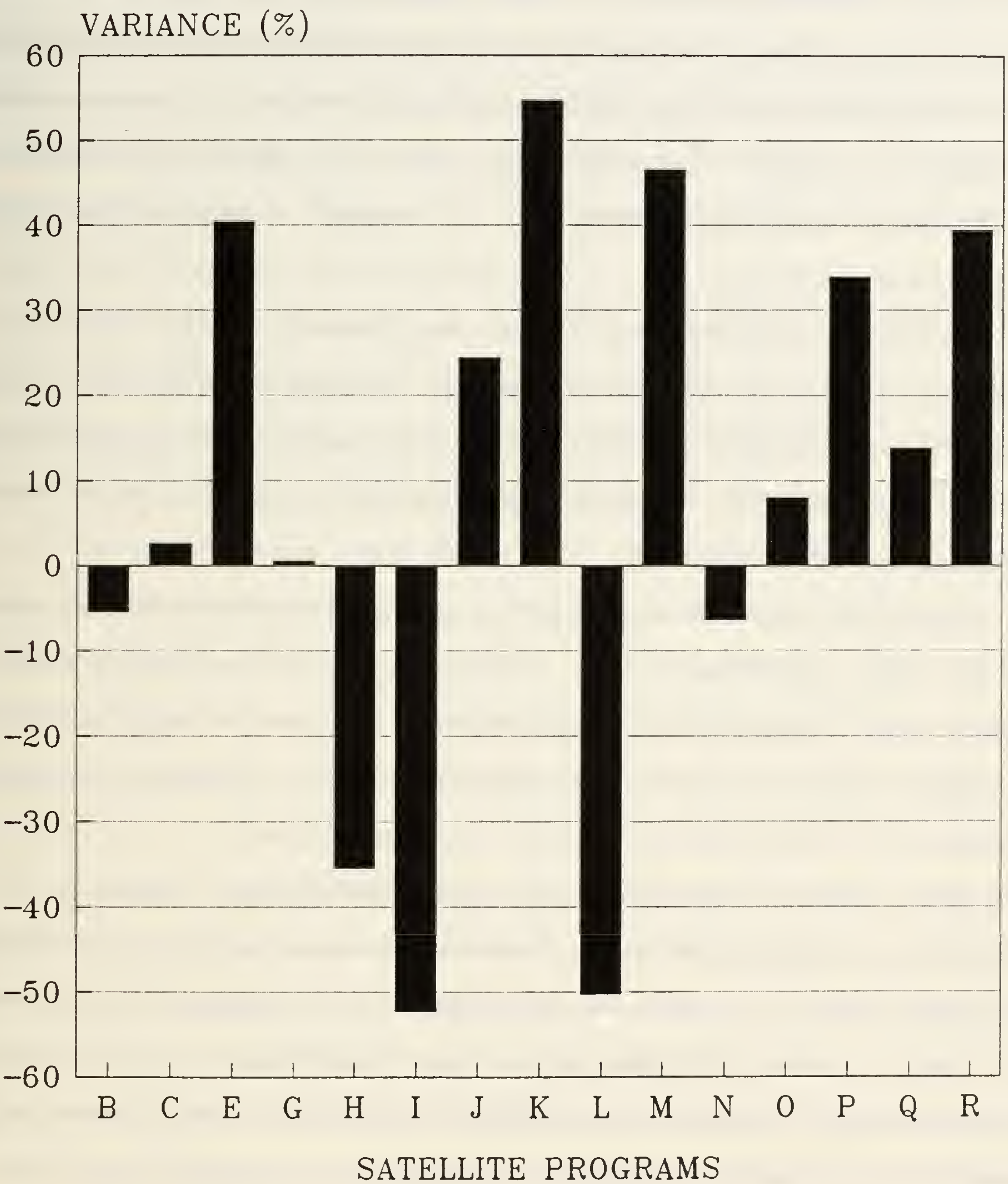
[15]Average (absolute) variance in Figure 4 is 27%. Model 2, Table 9 also provides a good prediction of production cost. Using Model 2 to predict production cost resulted in an average variance of 35%.

FIGURE 4
PRODUCTION COST VARIANCE



develop cost estimating approaches and models that are workable for both cost prediction and cost control.

Our first step was to identify technology determining characteristics. Technical expertise was necessary to develop relevant characteristics. Such characteristics should be goals of the development process, alterable by engineering development decisions, and ascertainable at an early stage in the development process. Factor analysis was used to reduce the number of technology characteristics to a number manageable during subsequent analysis.

Through a regression model, the factor scores were used to predict the year in which systems become operational. High explanatory ability of this model provided indirect confirmation that the factor scores appropriately reflected relevant dimensions of technology.

This regression was used to define a year-of-technology for individual systems, from which measures of the state of technology (STAND), the extension in technology beyond the current state of the art (ADVANCE) and the extent of technology embodied in each system (REACH) were developed.

The purpose of creating these technology measures was to facilitate prediction of the cost of developing new technological systems, and to offer a methodology for controlling such costs. It was therefore necessary to hypothesize and test for associations between the technical complexity of the development task and the level of activity required to complete the task.

Two variables, STAND and ADVANCE, reflecting technological complexity, were successfully used to predict development time. Development time was found to be positively related to both the state of technology at the time a development project was undertaken, and the extension in technology required.

Predicted and residual development time were used to predict development cost. Results indicated that development cost is not a smooth function of time; when completion drags on beyond the "natural" project time, cost increases more rapidly, consistent with time pressure influencing costs.

This two stage approach to estimating development cost was found to be superior to a direct production of cost from the technology variables, indicating that development time is an intervening variable between technological complexity and cost.

The two stage approach also permitted the creation of variance measures useful for controlling costs. The Variance Due to Time reflected the portion of the Total Cost Variance attributable to the cost consequences of time delays. The Cost Control Variance indicated the quality of cost control for projects.

Measures resulting from the analysis of the development phase were then used to predict production cost. Production costs were found to be related to the scope of the program, best captured by the actual ex post development cost. This result indicated that both the time and cost control variances during the development phase contain information useful in explaining subsequent production costs; i.e. cost "overruns" experienced during development tend to be permanent and reflected in higher production cost.

Lastly, the idea of a development "premium" was introduced to explain the ratio of development cost to production cost. Findings indicated that the greater the technological complexity of the system, the larger development costs are relative to production costs. This relationship was then used to determine expected production cost, a benchmark from which a production cost variance, useful in control of production cost, could be calculated.

The fundamentals developed in this study provide a workable methodology for measuring technological complexity and advances in technology in systems. The methods have also been shown to be effective in relating technology measures to the cost of development and production programs. The approach results in variance measures useful in the difficult task of cost control.

The approach was tested on only one set of data. However, measures developed at each stage of the analysis were used in subsequent stages, and at each stage hypotheses about the expected relationships between variables were confirmed. This provides some evidence of the internal consistency and logic of the approach. Of course future research applying similar methods to additional data sets would be beneficial.

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Appendix I

VARIABLES DESCRIBING SATELLITE TECHNOLOGY

Attitude Control System (ACS) variables:
- ACS1 -- Pointing accuracy (reciprocal).
- ACS2 -- Primary stabilization Method (coded: Spin = 0; moment, inertial, dual = 1).
- ACS3 -- Maneuverability (coded: no = 0, yes = 1).

Apogee Kick Motor (AKM) variables:
- AKM1 -- Specific impulse.
- AKM2 -- Propellent weight / Dry weight.

Communications variable:
- COMM -- Power required.

Electrical power systems variables:
- EPS1 -- Battery Capacity.
- EPS2 -- Beginning of life power / Array Area.
- EPS3 -- Array Topology (coded: body = 0, fixed = 1, movable = 2).

Mission or environmental variables:
- LIFE -- Design life.
- NHARD -- Degree of nuclear hardening.
- LAUNCH -- Launch method (coded: missile = 0, Shuttle, dual = 1).
- QUALS -- Percent of components that must be of "space" quality instead of merely "aircraft" quality.
- APOGEE -- A function of maximum orbital distance from earth, design life and quality.
- DESIGN -- Design life adjusted for quality.

Thermal variable:
- THERM -- Tolerable temperature range (maximum - minimum).

Tracking telemetry control variable:
- TTC -- Autonomous operating days.

Appendix II

This appendix describes the factor analysis process used to compress the 17 raw technology measures[16] down to four factor scores. The procedure used was part heuristic, part statistical. Principle components factor analysis with varimax orthogonal rotation was conducted on the original 17 variables. Variables with large (>.50) negative factor loadings on the first factor analysis run were eliminated since characteristics had to be consistently specified so that increasing values corresponded to greater technical difficulty.[17] This eliminated DESIGN, ACS3 and EPS2. QUALS was also discarded because it had no substantial positive factor loading (no loading greater than or equal to .50).[18] The remaining 13 variables were factored again and clustered onto four factors with 78.5% of the variance explained.

At this point the objective in eliminating variables became to maximize the percentage of variance explained.[19] In addition to substantial loadings on their principal factors, ACS1, TTC and LAUNCH had significant loadings in other columns. Through trying

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[16]Data was available for all 17 variables for each satellite with the exception of variable THERM for satellite R. The mean value of THERM was used for satellite R in the subsequent analysis.

[17]See Dodson and Graver [1969] for a further discussion of this constraint.

[18]For an excellent summary of variable selection criteria and "simple" matrix structure objectives see Kerlinger [1973, pp. 672-73].

[19]This is a common practical expedient in factor analysis. See Harman [1976, p. 185].

various combinations it was found that by eliminating ACS1 and TTC but retaining LAUNCH the variance explained reached a maximum of 81.7%. (Of course, this is not an optimization method. In general, no optimization methods exist for factor analysis. There is no guarantee that a superior solution could not be reached by some other sequence of steps. The authors can only report the steps taken in this particular analysis.) Factor loadings and eigenvalues from the final rotated factor matrix are shown in Table 11.

Factor Interpretation

The clustering of the variables and the strong loadings lead quite easily to conclusions as to the nature of the four factors that describe the technology embedded in a satellite.

Factor 1 can be labeled MISSION. To achieve a particular mission, design requirements must be specified reflecting the distance from earth (APOGEE), design life (LIFE) and launch mode (LAUNCH). While the variable COMM is actually required power for communications equipment, it should follow from mission specifications.

Factor 2 consists of two apogee kick motor variables. Since the apogee kick motor is used to achieve a particular orbit, we have labeled this factor ORBITAL.

Factor 3 consists of three variables reflecting ELECTRICAL POWER technology. Battery capacity (EPS1) and array topology (EPS3) are directly related to the technical sophistication of the electrical system. The primary stabilization method (ACS2)

TABLE 11

ROTATED FACTOR MATRIX

	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4
APOGEE	.9632	.0337	-.0891	.1204
LIFE	.9599	.0328	.0015	.0456
COMM	.8391	.1331	.3663	.0616
LAUNCH	.7376	.0485	.4279	.4189
AKM2	.0869	.9802	-.0465	.0820
AKM1	.0370	.9611	-.2015	.0516
ACS2	.1668	-.0800	.8055	-.3237
EPS3	.3438	.0127	.7822	.2536
EPS1	-.1284	-.2747	.5379	.0722
THERM	.1635	-.0866	-.1575	.8464
NHARD	.0917	.2131	.1706	.7602
EIGENVALUE	4.006	2.348	1.388	1.250

is indirectly associated with electrical power because the stabilization method has implications for array deployment which depends on array topology type.

<u>Factor 4</u> consists of two variables reflecting the <u>ENVIRONMENT</u> in which the mission is to be conducted. The temperature range (THERM) affects component design, while the degree of nuclear hardening (NHARD) is directly mission-determined.

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