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A MODEL FOR ESTIMATING THE COST IMPACT OF SCHEDULE PERTURBATIONS ON AEROSPACE RESEARCH AND DEVELOPMENT PROGRAMS

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16. ABSTRACT

The problem of determining the cost impact attributable to perturbations in an Aerospace R&D program schedule is becoming increasingly important as the availability of R&D funds diminishes. This memorandum develops the methodology from which a model is presented for updating Aerospace R&D cost estimates as a function of perturbations in program time.

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costs; costs estimating; cost model, cost data collection; cost data analysis; regression analysis; S-factor; schedule factor; schedule.

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A MODEL FOR ESTIMATING THE COST IMPACT OF SCHEDULE PERTURBATIONS ON AEROSPACE RESEARCH AND DEVELOPMENT PROGRAMS

SUMMARY

The long lead time and the tremendous cost associated with launch vehicle development limit the number of systems and therefore the amount of data available for establishing relationships that may be of value for predictive and evaluative purposes. This necessitates the need to have additional data in the form of available aircraft development data, so that through an appropriate relationship, the data may be of value for predictive purposes.

The proposed investigation will attempt to take the available data as mentioned above and through analytical methods establish a means of predicting the impact of schedule perturbations on R&D cost. Once established, these relationships will be of value in future planning. The proposed investigation will not attempt to be all encompassing; instead it will involve the schedule impact associated with the R&D portion of the program only. It is theorized that if this portion of a program can be predicted with some degree of accuracy, the burden of cost decision-making for the program manager will be significantly lessened.

The objectives of this research have been broken into three parts or phases. Phases one and two are illustrations of the current methodology available today for Cost Estimating Relationships (CERs). Phase three is being developed in this research.

The first phase is the determination of a functional relationship for predicting R&D cost as a function of an independent variable, namely, gross weight, dry weight, or thrust.

The second phase is the determination of a functional relationship for predicting R&D time as a function of R&D cost.

The third phase, and major objective of this research, is to develop a logical, systematic, step-by-step approach for updating R&D cost estimates for varying schedule requirements. This objective will be accomplished through the development of a model which predicts a factor for updating R&D cost estimates as a function of perturbations in R&D program time.

To summarize, the overall objective will be satisfied by the development of a model that has as the independent variable either a gross weight, dry weight, or thrust value within an acceptable range. From this independent variable, predictions of R&D cost and R&D time are obtained. Then with this R&D cost and R&D time, or others obtained from more sophisticated models, this model will predict a value for updating the original R&D cost estimate for varying schedule perturbations.

The problem to be investigated in this research may now be concisely stated as follows:

> Develop a systematic method for updating R&D cost estimates for various schedule perturbations.

The problem has now been defined sufficiently to proceed with the investigation.

INTRODUCTION

Man and society have always placed a high value on the ability to foresee the future. This is witnessed by the high prestige and position in history often afforded the seer — be he prophet, oracle, witch doctor, astrologer, or economist. Men who control or invest in business are probably as anxious to see beyond today's operations as the ancient Greek general was to find portents for success in the next day's skirmish. As society has become more sophisticated and competitive, many superstitions and even educated guesses have been found wanting. As a result, systems of analysis and predictions have been developed in a wide variety of fields. Forecasts in areas such as weather, political and economic trends, agricultural and industrial production, and Government spending provide guidance to major segments of society, and are often essential to everyday operations [1].

Partially as a result of this forecasting ability, within the last 40 years the United States has climbed from a poor fourth position to first place as the leader in Nobel prizes. We have developed one of the most expensive, complex, and sophisticated national research apparatuses in the world. Yet, as our world has become more complex, the United States now, perhaps predictably, seems to have reached a plateau in national support for science and technology.

Since 1968, Federal funds for Research and Development (R&D) have declined steadily both in number of dollars and in terms of the buying power of the dollar. In Fiscal Year (FY) 1971 less money was spent than in FY 1966. To be sure, that decline in funding coincides with the completion of several major scientific and engineering missions, such as the manned lunar landing. However, the real level of effort in R&D, taking into account the effect of inflation, has declined nearly 25 percent during the last four years [2].

During these austere times as R&D funds continue to decline, the forecasting of costs for programs, such as the NASA's upcoming space shuttle, space tug, High Energy Astronomy Observatory, or space station, becomes more and more critical to the existence of new programs. Good cost estimates are considered essential. In addition, the Congress of the United States, the source of all Government program funding, is beginning to ask the question "on what time scale?" in regard to R&D funding. Thus the scheduling, as well as the funding associated with the space effort, becomes a critical factor.

CHAPTER I

THE PROBLEM OF COST ESTIMATION

The cost-estimation field has developed rapidly, especially with the advent of electronic computers. However, the problem of integrating cost associated with a program and the schedule for the program has been very evasive to the researcher. Before solving the problem, it is necessary to formulate the problem so that constraints are imposed in such a way that a technique can be developed to provide a satisfactory solution to the problem.

A review of findings from studies undertaken by others appears to be a logical approach to the research problem. Numerous references were searched in an effort to find material useful for this investigation. The references can be catalogued into five categories, namely, purpose of cost estimating, model building, regression analysis, study rationale and statistical techniques, and development cost and development time studies. A discussion of these categories follows.

An early study by J. P. Large [3], The Rand Corporation, helped explain the purpose of cost estimating. Large states that over a period of years the final cost of a number of important weapon systems has been as much as ten times as high as the original estimate. Errors of this magnitude have caused a number of people to ask whether it is really possible to estimate R&D, investment, and operating costs of future systems (which cannot be completely defined in advance) with sufficient accuracy to use these estimates as a basis for major program decisions. In answering such statements, it must be recognized that a certain amount of uncertainty is inevitable in any action occurring in the future. The range of uncertainty is wide for future systems, and the further we peer into the future the wider this range becomes. Striving for a degree of accuracy that is inherently unattainable should be avoided. The primary purpose of cost analysis is comparison — to provide estimates of the comparative or relative costs of competing systems, not to forecast precisely accurate costs suitable for budget administration.

Many attempts have been made in recent years to develop acceptable cost-estimating models. The model used as a pattern for this investigation follows a study by J. S. McKnight [4], General Dynamics/Forth Worth, in which model building for cost-estimating purposes is described. The paramount objective in building the McKnight cost model was to meet the exacting requirements dictated by the long range plan for the model. To attain this objective, it was necessary for the model to have the capability of accurately costing not only Saturn-type launch vehicles but also advanced launch vehicle concepts. The model was based to a large extent on the experience of Saturn vehicles and that of their predecessors; however, the model also had the capability of costing new technologies, new launch vehicle concepts, new recovery concepts, etc. The cost model filled the requirements of an acceptable model in that it was usable and versatile, it had a built-in growth and updating capability, and the model was reasonably accurate.

A study by J. A. Stucker and R. M. Wyskida [5], NASA/MSFC, utilizing multiple regression on eight R&D launch vehicle programs to develop estimating equations for various subcategories R&D programs, was one of the early studies to consider multiple regression for predicting costs, rather than using simple regression. The study indicated that in most cases costs could not be adequately described by one variable alone. In this study estimating relationships were established for the following subcategories: engineering, manufacturing, tooling, test and program integration, and management. Although the study admittedly did not consider some factors which influence costs, such as schedule and inflation, the study is very useful in that considerable effort went into selecting some of the most satisfactory variables for regression analysis, e.g., gross weight, dry weight, and thrust.

Another study conducted by Wyskida [6] proved useful in the rationale and statistical techniques utilized. The study developed an approach for determining the proper capability-mix at a specific point during the growth phase of an R&D launch vehicle program. The objective was accomplished through the development of a model which represented four growth-phase, effort-expenditure categories (engineering, manufacturing, tooling, and quality assurance) through six interdependent ratios (engineering/manufacturing, engineering/tooling, engineering/quality assurance, manufacturing/tooling, manufacturing/

quality assurance and quality assurance/tooling). Wyskida theorized that if the proper capability-mix is achieved during the growth phase of the program, the program can be controlled. Much of the work performed by Wyskida was directly applicable to the current investigation.

Considerable effort has gone into the last category, development cost and development time studies. A Study by A. W. Marshall and W. H. Meckling [7] resulted in the tentative conclusion that technological uncertainty is one probable cause of development cost overruns but by no means the only cause. Their study found that the average production cost and development time variances were an increasing function of the size of the technology advance increases — programs with small advances had an average factor of 1.4, programs with medium advances 1.7, and programs with large advances an average factor of 3.4. Note that Marshall and Meckling were concerned with production cost factors, whereas this investigation is considering development cost factors.

A similar study conducted by M. J. Peck and F. M. Scherer [8] indicates that of 11 R&D launch vehicle programs studied, 7 exceeded the scheduled development time, 3 were on time, and 1 had a shorter development time than originally estimated. The average development time factor (actual time divided by original time estimate) for the 11 R&D programs was 1.36, or the R&D time was on the average 36 percent longer than the original time estimate. Another factor developed in the same study was the development cost factor. Of the 11 R&D launch vehicle programs studied, 10 exceeded the scheduled development cost, none met expectations, and 1 had a smaller development cost factor than originally estimated. The average development cost factor (actual cost divided by original cost estimate) for the 11 R&D programs was 3.2, or the R&D development cost was on the average 3.2 times more costly than originally estimated.

Another study conducted by G. E. Nichols [9], Jet Propulsion Laboratory, used the method previously outlined by Peck and Scherer to compare the deviation experienced in schedule and cost for 10 unmanned spacecraft programs. Of the 10 programs, 7 exceeded the scheduled development time, 3 were on schedule, and none had a shorter development schedule than originally estimated. The average development time factor for the 10 unmanned spacecraft programs was 1.44. The development cost factor was also developed for these same programs. Of the 10 programs, 7 exceeded the estimated development cost, 1 had the estimated cost, and 2 had a smaller development cost factor than originally estimated. The average development cost factor for the 10 unmanned spacecraft programs was 2.44.

From the studies reviewed, it is evident that considerable effort has been expended in the estimation of R&D cost and R&D time; however, none of the studies have addressed the problem of schedule impact upon cost. An analytical method for estimating the impact of schedule perturbations on R&D cost would be very useful to management for planning purposes. The present approach to such planning is primarily subjective and is based upon the intuition and experience of management personnel. The proposed method of determining the impact of schedule perturbations on R&D cost should provide an objective and quantitative approach to assist the manager in the solution of this problem.

CHAPTER II

MODEL FORMULATION

The researcher is confronted with the problem of determining the proper model formulation early in the investigation. The nature of the problem itself greatly influences the particular model formulation. The model can be based upon a controlled experiment, such as would be conducted in a laboratory, or it may be based upon data obtained from a number of similar situations. The latter is the type normally found in the aerospace environment where new long range space systems are developed.

The literature defines a model in various ways. D. W. Miller and M. K. Starr define a model as a representation of reality that attempts to explain some aspect of it [10]. M. Ezekiel and K. A. Fox [11] are more descriptive when they say: "An algebraic equation which expresses the relation logically expected between or among two or more variables is sometime called a "model" of the relationships. Such a model is a mathematical expression or the hypothesis according to which the observed data will be examined to see whether or not the facts support the hypothesis, and to determine the value of the statistics."

Since a model is a mathematical representation of a situation, it is always less complex than the reality itself; but it is sufficiently complex to approximate the aspects of the situation being investigated. The structure of the research model and the research solution approach will be described in this chapter.

Structure of the Model

Models used to display estimating relationships are of three principal forms: mathematical, which utilizes symbols in the form of mathematical equations to represent the system being studied; graphic, which is a visual or pictorial representation of the system; and tabular, which utilizes one set of factors or phenomena to represent those of the system [12]. A mathematical model utilizing equations to express systems will be the form used in this research.

The particular mathematical model for this research is a launch vehicle cost model. The approach to the launch vehicle cost model development was patterned after a model developed by J. S. McKnight [4]. In developing the model a formulation is followed which satisfies the requirements imposed on the model in terms of its intended use and application. On the basis of the criteria of use and application, the basic model structure and the key building blocks are selected for the final development of a comprehensive and versatile model. The underlying approach used to develop the model is outlined in Figure 1. In the figure, the heavy arrows represent the logical path of accomplishment in the completion of key tasks.

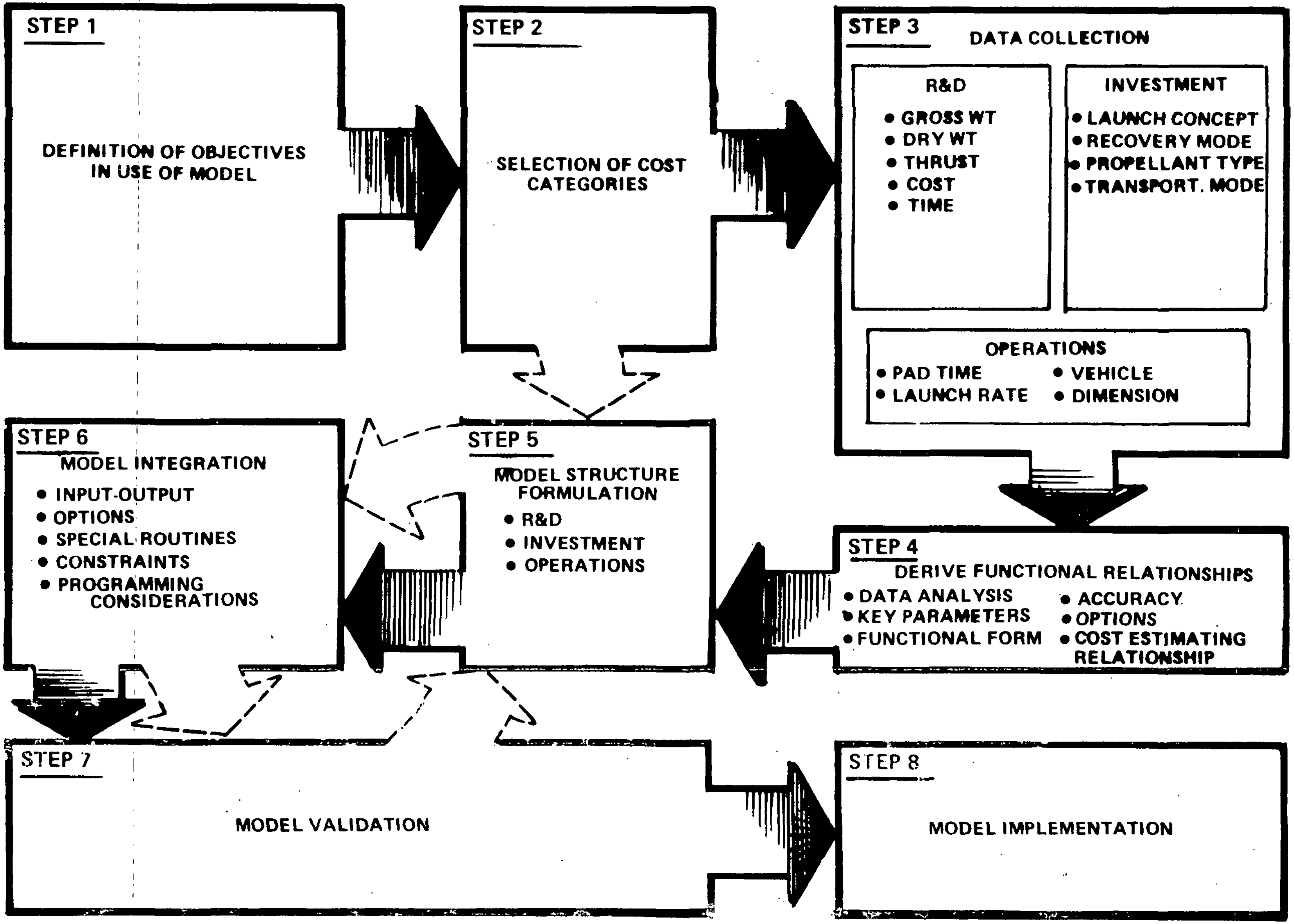


FIGURE 1. LAUNCH VEHICLE COST MODEL DEVELOPMENT FLOW CHART

With proper planning, several of the steps may be undertaken concurrently to meet schedule requirements, although preferably, the steps are completed sequentially. The data interchange and feedback among the various steps indicated by dotted arrows are characteristic of the iterative process employed in good model development.

The following is an outline of the basic tasks accomplished in the development of the model. More detailed discussions are given in subsequent chapters as the technical approach which was followed in accomplishing those tasks is explained:

a. Step 1 — Definition of Objectives in Use of Model

   The objective of the model is to develop a systematic approach for updating R&D cost estimates for varying schedule requirements.

b. Step 2 — Selection of Cost Categories

   The cost category selection is determined as a result of cost objectives and historical data available. The cost categories selected provide maximum flexibility in cost analysis and are responsive to variances in design and operational parameters.

c. Step 3 — Data Collection

Following the definition of cost categories, an intensive data search is undertaken to gather and assimilate all applicable information related to the selected categories. Data collection will not be completed until all raw data have been consistently interpreted, collated, and refined. Data too vague or gross to fit the defined cost categories will be discarded.

d. Step 4 — Derive Functional Relationships

Functional relationships are equations which describe mathematically the mechanisms that link design and performance to cost. These relationships are derived principally through a regression analysis of applicable data. When the functional relationships are systematically integrated into the basic submodels, the basic structure of the cost model is formed.

e. Step 5 — Model Structure Formulation

In formulating the model structure, consideration was given to the major series of events required in the development and use of a launch vehicle.

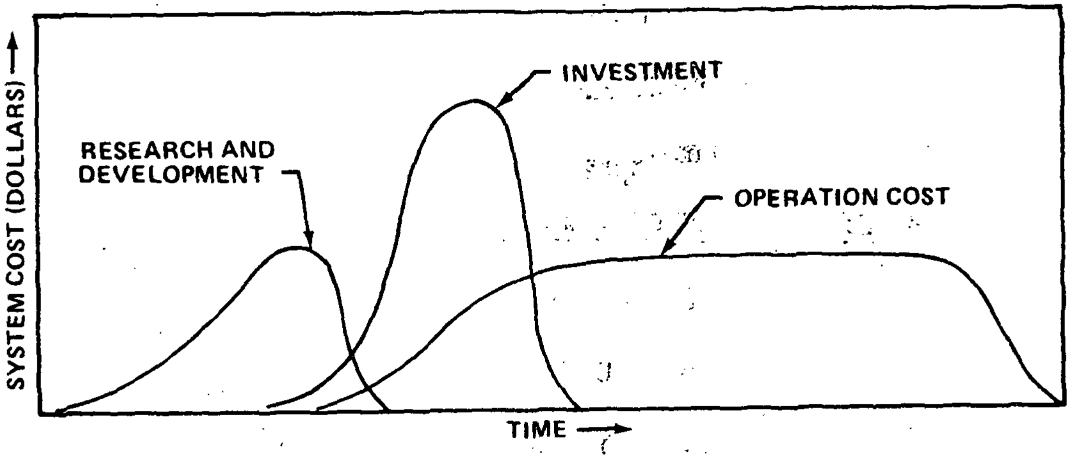
The elements of a typical launch vehicle program are broken into three categories: R&D, investment, and operations. Figure 2 illustrates these categories with time phasing of system cost over the lifetime of a project. These three categories are defined as follows:

1. R&D — Outlays for basic research and exploratory development plus developmental activities required to develop new capabilities to the point where they are ready for introduction into the active inventory.
2. Investment — The one-time outlays required to introduce new capabilities into the active forces.
3. Operating — The recurring costs that must be incurred to maintain and operate capabilities after they have been initially introduced into the active inventory [9].

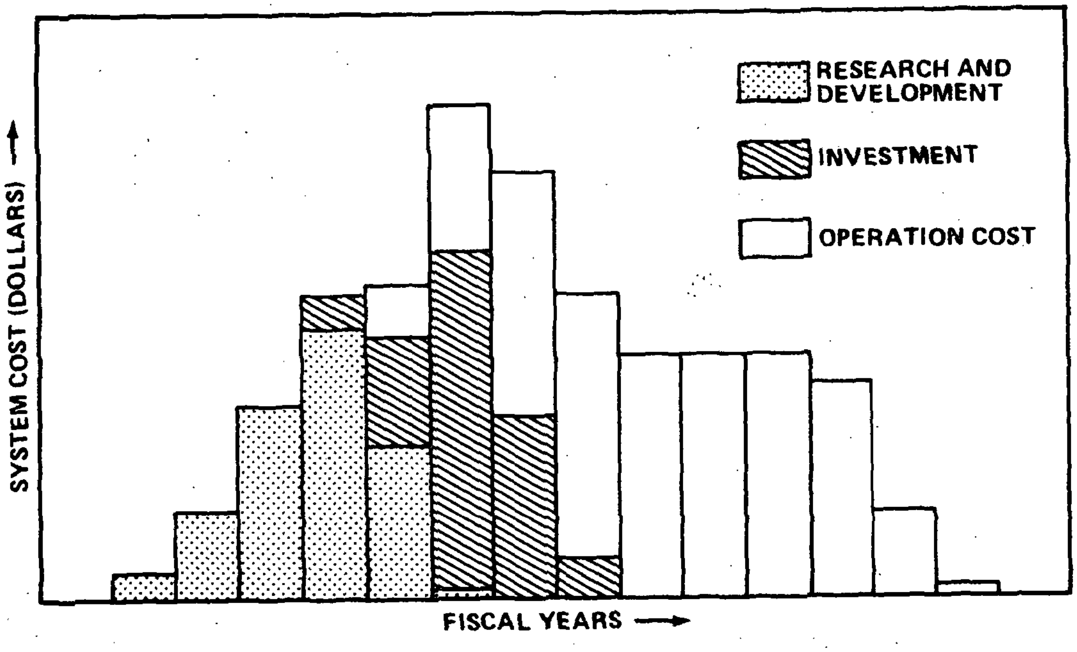
However, since it is the purpose of this research to illustrate a concept, the first category, R&D, will be the only one investigated. It is immediately evident that the concept could also be extended to cover investment and/or operations.

f. Step 6 — Model Integration

The complete model will be integrated after the formulation of the basic model structure. As the



a. SYSTEM COSTS TIME-PHASING (IDEALIZED CURVES)



b. SYSTEM COSTS TIME-PHASING (BY FISCAL YEARS)

FIGURE 2. SYSTEM COST TIME PHASING

three phases, or submodels, mentioned previously, are formulated, other subroutines, options, and program constraint factors will emerge for consideration, and those which are found to be valuable additions to the overall model will be integrated into the cost model.

g. Step 7 — Model Validation

The SNAP Multiple Regression Analysis Program for use on the UNIVAC 1108 is the computer program used in the model. This program is used to select the functional relationships required for the program. The model will be thoroughly checked through the use of a sample problem that serves to demonstrate the usefulness of the concept for budget or mission planning.

h. Step 8 — Model Implementation

The model implementation is the actual utilization of the model to determine predictive schedule slip factors for R&D Programs.

Program cost estimates used in Government as well as industry today utilize CERs. A simple definition of a CER is: A statement of how one or more variables affect another. In certain instances, a simple factor type-relationship may exist that can be expressed as a single number. In estimating pay allowances, for example, a simple multiplier can be applied to the number of people to generate an estimate of their annual pay. On the other hand, cost-estimating relationships can be considerably more complicated where there is intricate interplay between two or more variables and another variable such as the relationship between launch vehicle thrust and cost and the cost of storage for that launch vehicle. These CERs for costs down to the subsystem level are programmed into high-speed computers, and in a matter of minutes numerous calculations are performed to derive the cost estimates. These estimates are made on the assumption that the program will be completed in some k number of months although the months may never be considered in developing the CERs and certainly will be no part of the calculation. If a compression or decompression of the schedule is ordered, there is no indicator to help the estimator compute the additional cost involved.

Hence, this research will attempt to illustrate a concept which could be utilized as a management tool to estimate the impact of schedule perturbations on cost. However, to make the model more meaningful, this research will include in a cursory fashion cost-estimating relationships, developed from the data necessary in the development of the schedule factor or S-factor model, to predict R&D cost and R&D time. Basic historical data or data obtained from more sophisticated models should be utilized, where possible, for the first and second phase of this model. The third phase of the model will be developed in this research. The three phases of the research will be explained using the three graphs (A, B, C) in Figure 3.

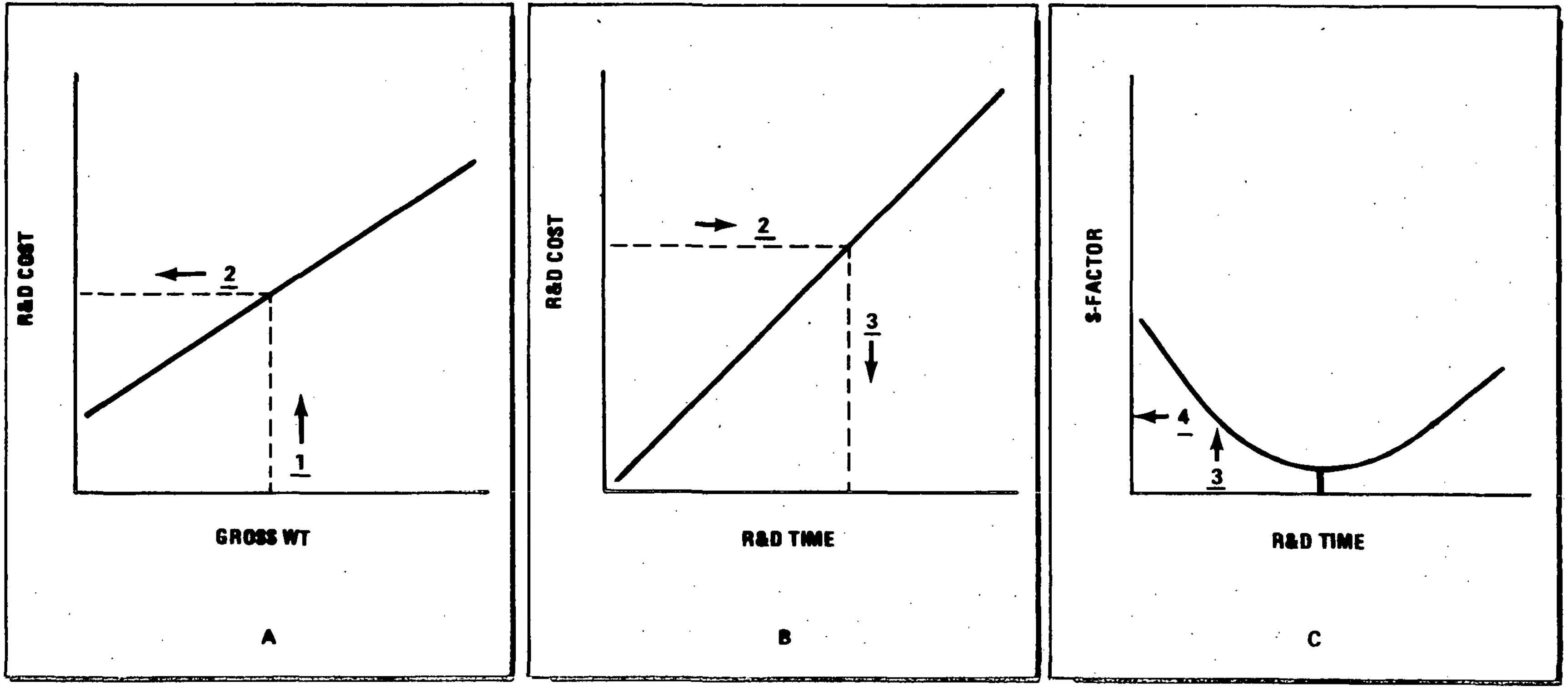


FIGURE 3. ESTABLISHING A SCHEDULE FACTOR

Graph A, phase one of the model, represents a CER determined by regression analysis. As illustrated on the graph the first input is gross weight (gross weight was chosen for illustration; CERs for dry weight and thrust will also be provided). The gross weight input 1 yields R&D cost as an output 2:

R&D Cost = $f(X_i)$,

where

$i = 1, 2, \text{ or } 3$

and

1 = gross weight,

2 = dry weight,

3 = thrust.

Next, as illustrated in graph B the R&D cost 2 calculated from graph A becomes the independent variable and predicts R&D time 3:

R&D Time = f(R&D Cost).

(The dependent variable, time, would normally be plotted on the ordinate; however, since all other graphs used in this research utilizing the parameter, R&D cost, are plotted on the ordinate, it was decided to keep this factor in a constant location.)

Then, using time 3 as the independent variable in graph C, the schedule factor or S-factor 4 can be determined for each year. Interpolation between years permits monthly estimates. The S-factor would then be multiplied by the initial R&D cost estimate to find the adjustment required for schedule changes.

Graph A and B in the above example are required only as a means of establishing an R&D cost and an R&D program time. If these factors had previously been determined by other means, graph C could immediately be utilized to determine the S-factor.

The variables necessary in the development of the relationships shown in Figure 3 are defined below:

Gross weight	The stage/vehicle weight in pounds including electrical, instrumentation, propulsion system (including engine and propellant), and structures
Dry weight	The stage/vehicle empty weight in pounds including electrical, instrumentation, propulsion systems (including engines) and structures
Thrust	The total stage/vehicle thrust in pounds
R&D cost	The expense incurred over the R&D time portion of a contract. Includes all nonrecurring costs
R&D time	The period beginning with program approval and concluding when the vehicle is ready for operational use (5, p. 65)
S-factor	A multiplier of R&D cost estimates given as a function of schedule compressions or decompressions.

Solution Approach

Statistics have long been used as a means of establishing relationships between variables. When information is available on two or more related variables, it is natural to seek a means of expressing the variables in the form of some functional relationship. These relationships are often used by management to form the basis for executive decisions.

In addition, it is desirable to know the strength of the relationship. We seek a mathematical function which tells us how the variables are interrelated (regression method) but also wish to know how precisely the value of one variable can be predicted if we know the values of the associated variables (correlation method). Regression methods are used to determine the best functional relation among the variables, while correlation methods are used to measure the degree to which the different variables are associated [13].

Several regression methods are outlined in the literature. For this research, the method of least squares will be utilized. This relationship is determined by fitting a curve to the data points so that the sum of the squares of the differences from each point to the curve is a minimum.

Regression is considered as multiple regression when more than two variables are involved and simple regression when only two variables are to be considered. The general form of the model is stated as:

$$Y = b_0 + b_1 X_1 + \ldots + b_n X_n .$$

Two statistical measures associated with multiple regression are the t test (often called Student's t) and the multiple correlation coefficient r. The t test is first used to test the coefficient b_i ($i = 1$ to n; n = number of observations) to determine whether the coefficient is significantly different from zero. The hypothesis and the equation associated with the t test for the coefficient b_i are as follows:

Null Hypothesis $H_0: b_i = 0$, where $i = 1$ to n ,

Alternate Hypothesis $H_1: b_i \neq 0$,

Test Equation $$t = \frac{\text{Coefficient } (b_i)}{\text{Standard Deviation of Regression Coefficient}} .$$

The multiple correlation coefficient r measures the degree to which different variables are associated through the following equation:

$$r = \sqrt{\frac{\text{Variation Due to Regression}}{\text{Total Variation}}} .$$

A positive correlation coefficient $+r$ indicates positive or direct correlation while a negative correlation coefficient $-r$ indicates negative or inverse correlation. Direct dependence of two variables would yield a value of $r = +1$ whereas direct inverse dependence yields a value of $r = -1$. No correlation or dependence produces a value of $r = 0$.

After the test for the multiple correlation coefficient has been performed, the question arises as to the value of r being different from zero. The t test is also used to perform this test. The hypothesis and the equation associated with the t test for the r values are as follows:

Null Hypothesis H_o: $r = 0$

Alternate Hypothesis H_1: $r \neq 0$

Test Equation $t = r \sqrt{\frac{n-2}{1-r^2}}$.

Only regression coefficients and correlation coefficients meeting the 0.90 significance level will be considered acceptable for this research.

The calculations required for the solution of regression analysis are tedious and very time consuming. The margin for error is great even with the aid of a calculator. Fortunately several computer programs are available which solve the multiple regression problem. The one utilized in this research is the SNAP Multiple Regression Analysis Program which is executed on the UNIVAC 1108 System. (Appendix A gives a description of the SNAP Program.)

Model Assumptions

The statement of the assumptions made during a period of investigation is necessary if the model is to be understood. It further helps to prevent any misunderstanding which may result after the findings are presented. The assumptions associated with this model are as follows:

1. The data collected come from typical programs which possessed average cost and schedule changes. The data are assumed accurate and complete as collected. (Adjustment of R&D cost to constant FY 1971 dollars compensates for the effect of inflation among programs.)

2. All programs received similar priority during the R&D portion of the program.

3. The model will be used to predict only values that fall within the range of the model.

4. The model is presented to illustrate the concept rather than presenting the S-factor as final. As additional data are made available, computation of an S-factor for launch vehicles or aircraft could be performed. Greater confidence could then be placed in the S-factor.

5. The model assumes that the cost impact for schedule changes in aircraft is of the same magnitude as for launch vehicles.

6. The dependent variable data are derived from a population with a normal distribution.

With the model assumptions stated and the general concept outlined, it is now possible to begin the model development. The reader should, however, bear in mind that the primary objective of developing the model herein is to show the method used in the development process, rather than to produce a completely valid model for immediate application. It should be possible, using the methodology developed in this research, to develop a more accurate model as program histories are made available.

CHAPTER III

MODEL DEVELOPMENT

The requirements placed upon a cost model today fall into three categories. First of all, a cost model must be developed so that it is subject to ready manipulation. This means that the model must be a simplification of reality, but care must be exercised not to oversimplify in those areas of the problem that are critical to the planning process the model is designed to serve. In other words, the model must be sufficiently detailed in those critical areas to be responsive or sensitive enough to clearly reflect cost differences among the key alternatives under consideration. The second key consideration for a cost model is the matter of reasonably quick response time. If a planning exercise is to examine a fairly wide range of alternative force structures, the cost-estimating procedure must be able to estimate the cost impact of each of the alternatives in a timely fashion. The planner cannot wait several weeks for one of the alternatives to be costed out. The third requirement placed on cost models today is that they be readily adaptable to high-speed electronic computers. Not only has the computer speeded up the cost-estimating process, the accuracy is much improved over a purely manual process. The output from computers can also be sliced in a number of ways to permit maximum utilization of the data [14].

Data Collection

The collection of empirical data for launch vehicles was a relatively uncomplicated procedure since the NASA records are for the most part available to the public; however, the empirical data associated with launch vehicles of other Government agencies are difficult to obtain because of the classified nature of their programs. After a thorough search, empirical data as required for this investigation were available for 12 launch vehicle programs. In order to perform the investigation, a larger sample size was required; therefore, aircraft data were also collected using the same parameters as for the launch vehicles. The collection of data for aircraft was difficult and time consuming. Most corporations consider their data corporation proprietary and are reluctant to release data under any circumstances. The record keeping also varies from corporation to corporation; however, after considerable research 24 aircraft programs were determined to possess sufficient data to be included in the investigation. Thus, a total of 36 programs were available for model development purposes.

The data accumulated reflects programs and costs incurred at different times during the past 20 years. To eliminate the effects of the time value of money and the significant increase in price levels over this period of time, it was necessary to convert actual dollars to a fixed or constant year dollar value. For the purpose of this research, the 1971 dollar value has been selected as the standard. Indices as used by the Aerospace Corporation for use in adjusting historical cost data to 1971 dollars are given in Table I [15]. Column one gives the aircraft price index from 1951 to 1971 while column two gives the missile and spacecraft price index from 1958 to 1971. The difference between the aircraft price index and the missile and spacecraft price index is largely accounted for by the difference in labor costs for both the professional and production workers in the aircraft and missile and spacecraft field.

Data collected for the 36 programs are presented in Table II. The data include: R& D program time, gross weight X_1, dry weight X_2, thrust X_3, and R& D cost (adjust to 1971 dollars). The data are presented in groups of data that fell within 12-month or 1-year periods (37 to 48, 49 to 60, ----, 133 to 144). No data fell within the 109- to 120-month period. This presents no insurmountable problem, however, since interpolation over this period is permissable. These groupings are required later in the research to determine the S-factor. The original data, which are considered sensitive, were coded. This does not affect the validity of the data in any way since the relative relationships remain unchanged.

TABLE I

FACTORS TO CONVERT COST TO CONSTANT 1971 DOLLARS

Year	Aircraft Price Index	Missiles and Spacecraft Price Index
1951	2.30	
1952	2.10	
1953	1.99	
1954	1.91	
1955	1.83	
1956	1.76	
1957	1.69	
1958	1.62	1.62
1959	1.52	1.57
1960	1.46	1.53
1961	1.42	1.46
1962	1.38	1.40
1963	1.34	1.32
1964	1.30	1.28
1965	1.27	1.22
1966	1.23	1.18
1967	1.17	1.14
1968	1.12	1.11
1969	1.07	1.07
1970	1.03	1.03
1971	1.00	1.00

TABLE II

ORIGINAL PROGRAM DATA

Program	R& D Time (Months)	Gross Weight X_1 (K lb)	Dry Weight X_2 (K lb)	Thrust X_3 (K lb)	R& D Cost (M $)
A-1 (LV)	37	108.23	10.72	150.00	482.10
A-2 (LV)	44	111.00	8.99	152.00	364.50
A-3	44	33.00	14.86	11.35	180.00
A-4	37	51.70	28.50	17.10	40.40
A-5	42	34.50	24.00	24.50	87.40
A-6	47	127.20	60.00	18.00	178.10
A-7	37	10.17	6.97	2.95	30.80
B-1	60	91.50	44.00	37.00	267.20
B-2	58	170.00	22.00	24.00	98.40
B-3	56	38.00	12.00	5.70	29.10
C-1	65	450.00	177.80	10.50	251.40
C-2	63	22.00	8.40	7.80	96.30
C-3	63	155.00	72.89	16.20	150.10
C-4	63	80.00	49.41	34.00	42.10
D-1 (LV)	81	34.63	3.63	30.00	192.60
D-2	79	706.60	321.00	41.10	444.00
D-3	79	266.00	134.20	21.00	220.00
D-4	79	34.83	21.00	11.70	46.30
E-1 (LV)	91	981.99	85.29	1640.00	472.40
E-2 (LV)	91	1015.84	102.50	1500.00	425.10
E-3 (LV)	86	62.70	9.60	78.00	122.10
E-4	95	31.30	13.00	50.00	87.60
E-5	86	24.80	12.78	14.80	33.00
E-6	91	6.57	4.06	1.84	21.10
F-1 (LV)	100	114.47	12.70	90.00	362.70
F-2 (LV)	98	255.90	23.35	230.00	430.80
F-3 (LV)	100	226.00	16.60	300.00	652.70
F-4	102	11.76	7.41	3.85	21.50
H-1	130	49.64	24.70	20.28	361.80
H-2 (LV)	126	262.56	25.91	230.00	489.40
H-3	121	28.20	16.00	16.00	46.70
H-4	125	51.00	25.37	15.00	409.60
I-1 (LV)	137	4638.42	286.32	7500.00	634.90
I-2 (LV)	137	1074.93	80.34	1000.00	784.50
I-3	135	521.10	231.20	33.00	373.90
I-4	140	163.00	55.60	15.60	226.70

Data Analysis

The data analysis phase of the investigation requires that a step-by-step plan for completing the analysis be followed closely. The desired objective of this research was to determine a model for estimating the cost impact of schedule perturbations on aerospace research and development programs. The research was subdivided into three separate and distinct phases. Each phase, however, was completed using the same data required to compute the S-factor. The research is presented in such a fashion that a complete cycle is illustrated. The CERs as used by the estimator are presented in phase one and phase two to determine an R&D cost estimate and R&D time estimate. Phase three is then presented with a graph of time as the independent variable and an S-factor as the dependent variable. The researcher would therefore be able to input a parameter such as gross weight, dry weight, or thrust and through a series of computations determine an S-factor that could be multiplied by an original cost estimate to determine the impact of a schedule perturbation on the original cost.

After the expenditure of considerable time and effort, it was determined that launch vehicle data and aircraft data were not directly compatible. A method had to be devised to convert aircraft data to launch vehicle data. It was determined that the parameter that remains constant on a vehicle, whether it is launched vertically or takes off horizontally, is the gross weight. In turn, since dry weight is a component of gross weight, the dry weight was also considered a constant. The parameters that change are the thrust and the R& D cost. Both are higher for launch vehicles than aircraft of comparable gross weight.

The conversion of aircraft to launch vehicle data was ruled out after an examination of the program data. There were only 12 launch vehicle programs and 24 aircraft programs. The 12 launch vehicle programs were distributed over the 8 time intervals such that some time intervals had one or more launch vehicles and others had none. This would present a problem later in the investigation for the time intervals that had only aircraft data. Without supplemental launch vehicle data to mix with the converted aircraft data, the equation for the aircraft data remains the same straight line as that originally established for certain time intervals.

It was reasoned that since there were 24 aircraft programs and only 12 launch vehicle programs, it would suffice to convert the launch vehicle programs to aircraft programs. Utilizing this method, no particular year consists entirely of launch vehicle data. This would also produce sufficient data to illustrate the concept. S-factors for launch vehicles could then be computed using this model to illustrate the concept as sufficient data are made available.

The researcher realizes that the approach described for converting launch vehicle data to aircraft data to form hybrid data is less than the optimum situation. Because of a lack of sufficient data for either launch vehicles or aircraft, but particularly for launch vehicles, it was determined to be worthwhile to present the concept using hybrid data. As more launch vehicle data or aircraft data are made available, one or the other should be used to determine S-factors rather than combining the two as presented in this research. This should in no way invalidate the concept as presented. However, with these recognizable weaknesses, there is reasonable certainty in the validity of the statistical methods.

A logarithmic transformation applied to both the dependent and the independent variable of the aircraft data afforded the predictive equations necessary to convert the launch vehicle data to aircraft. These functional relationships are presented in Table III.

TABLE III

REGRESSION ANALYSIS FOR LAUNCH VEHICLE CONVERSION TO AIRCRAFT

Functional Relationship	r.c. Test t_{cal}	r	r Test t_{cal}	Degree of Freedom	Table $t_{0.90}$	Null Hypothesis
$\ln(X_3) = 0.89 + 0.43 \ln(X_1)$	3.98	0.65	4.01	22	1.72	Reject
$\ln(\text{R\&D Cost}) = 2.13 + 0.60 \ln(X_1)$	5.24	0.74	5.16	22	1.72	Reject

The t tests were performed on both the regression coefficient (designated r.c. Test in the table) and the correlation coefficient (designated r Test in the table). The hypotheses associated with the regression coefficient t test are as follows:

Null hypothesis

H_o : The gross weight coefficient is not significantly different from zero.

Alternate hypothesis

H_1 : The gross weight coefficient is significantly different from zero.

The hypotheses associated with the r test are as follows:

Null hypothesis

H_o : The correlation coefficient is not significantly different from zero.

Alternate hypothesis

H_1 : The correlation coefficient is significantly different from zero.

Utilizing these equations, the launch vehicle data, identified on Table II by LV, for thrust and R&D cost, was modified to be compatible with the aircraft data. Program A-1 will be utilized to illustrate the use of these equations for converting the launch vehicle data to aircraft data.

Program A-1: $X_1 = 108.23$

$\ln (X_1) = 4.68$

The following equation predicts aircraft thrust as a function of launch vehicle gross weight.

$$\ln(X_3) = 0.89 + 0.43 \ln(X_1)$$

$$= 0.89 + (0.43)(4.68)$$

$$= 2.91$$

$$X_3 = 18.38$$

Then, the following equation predicts aircraft R&D cost as a function of launch vehicle gross weight utilizing Program A-1 data:

$$\ln(\text{R\&D Cost}) = 2.13 + 0.60 \ln(X_1)$$

$$= 2.13 + (0.60)(4.68)$$

$$= 4.95$$

$$\text{R\&D Cost} = 141.13$$

The data as presented in Table IV reflect the changes to the launch vehicle data. The predictive model will be the next step in the investigation.

Predictive Model Development

In most physical sciences, relationships are commonly determined by controlled experiments. In the social sciences and in certain physical sciences such as astronomy, controlled experiments may be impossible or at least very difficult. Relationships must in such cases be discovered by analyzing the available data. The tool that was devised to accomplish this is the modern regression or correlation analysis. Often laboratory conditions cannot be set up that will exactly reproduce conditions in the plant. Consequently, the researcher is frequently in the position of the social scientist

TABLE IV

ADJUSTED PROGRAM DATA

Program	R& D *Time* (Months)	*Gross Weight* X_1 (K lb)	*Dry Weight* X_2 (K lb)	Launch Vehicle to Aircraft	
				Thrust X_3 (K lb)	*R& D Cost* (M $)
A-1	37	108.23	10.72	18.38	141.13
A-2	44	111.00	8.99	18.58	143.29
A-3	44	33.00	14.86	11.35	180.00
A-4	37	51.70	28.50	17.10	40.40
A-5	42	34.50	24.00	24.50	87.40
A-6	47	127.20	60.00	18.00	178.10
A-7	37	10.17	6.97	2.95	30.80
B-1	60	91.50	44.00	37.00	267.20
B-2	58	170.00	22.00	24.00	98.40
B-3	56	38.00	12.00	5.70	29.10
C-1	65	450.00	177.80	10.50	251.40
C-2	63	22.00	8.40	7.80	96.30
C-3	63	155.00	72.89	16.20	150.10
C-4	63	80.00	49.41	34.00	42.10
D-1	81	34.63	3.63	11.24	71.02
D-2	79	706.60	321.00	41.10	444.00
D-3	79	266.00	134.20	21.00	220.00
D-4	79	34.83	21.00	11.70	46.30
E-1	91	981.99	85.29	47.63	533.10
E-2	91	1015.84	102.50	48.33	544.10
E-3	86	62.70	9.60	14.52	101.56
E-4	95	31.30	13.00	50.00	87.60
E-5	86	24.80	12.78	14.80	33.00
E-6	91	6.57	4.06	1.84	21.10
F-1	100	114.47	12.70	18.83	145.97
F-2	98	255.90	23.35	26.65	237.05
F-3	100	226.00	16.60	25.26	219.95
F-4	102	11.76	7.41	3.85	21.50
H-1	130	49.64	24.70	20.28	361.80
H-2	126	262.56	25.91	26.95	240.74
H-3	121	28.20	16.00	16.00	46.70
H-4	125	51.00	25.37	15.00	409.60
I-1	137	4638.42	286.32	93.09	1358.83
I-2	137	1074.93	80.34	49.52	562.97
I-3	135	521.10	231.20	33.00	373.90
I-4	140	163.00	55.60	15.60	226.70

and astronomer, in that he must take the data as he finds them. Regression analysis is thus a very useful tool of research [16].

The predictive model development was accomplished in three phases. The UNIVAC 1108 computer with the SNAP - Multiple Regression Analysis Program was utilized to determine the predictive equations. In addition to computing the least squares fit of a line or curve to sample points, other statistics were also computed. Additional statistics include sum of squares, means, total variation, standard deviation, cross products, correlation coefficients, regression coefficients, sum of squares caused by regression, variance, and t value.

The first phase of the predictive model development was to utilize the 36 data points as presented previously in Table IV to predict R& D cost as a function of some independent variable or variables. The following relationships were tested:

1. R& D cost versus gross weight
2. R& D cost versus dry weight
3. R& D cost versus thrust
4. R& D cost versus gross weight and thrust
5. R& D cost versus dry weight and thrust

After testing the correlation coefficients for the above R& D costs as a function of the given parameters, the decision was made that functional relationships for the first three relationships would be presented to make the model as comprehensive as possible. These functional relationships are presented in Table V. The choice of the functional relationship used with the model is left to the discretion of the user.

TABLE V

REGRESSION ANALYSIS FOR PHASE I (NO TRANSFORMATION)

Functional Relationship	r.c. Test t_{cal}	r	r Test t_{cal}	Degree of Freedom	Table $t_{0.90}$	Null Hypothesis
R&D Cost = 126.38 + 0.29X_1	13.72	0.92	13.69	34	1.69	Reject
R&D Cost = 97.37 + 2.21X_2	5.66	0.70	5.72	34	1.69	Reject
R&D Cost = -54.03 + 11.72X_3	8.90	0.84	9.03	34	1.69	Reject

The null hypothesis associated with the regression coefficient t test is stated as follows:

H_o : The coefficient of X_i is not significantly different from zero.

The alternate hypothesis becomes:

H_1 : The coefficient of X_i is significanly different from zero.

The null hypothesis associated with the r test is stated as follows:

H_o : The correlation coefficient is not significantly different from zero.

The alternate hypothesis becomes:

H_1 : The correlation coefficient is significantly different from zero.

The equations presented in Table V have no transformation on the dependent or independent variable and are, therefore, linear in form. A graph of each functional form is presented in Figure 4.

Phase one of the model is now complete. A choice of functional relationships to predict R& D cost based upon vehicle gross weight, dry weight, or thrust is now available for use in the model.

The second phase of the predictive model development was to again use the 36 data points as presented in Table IV to predict R&D time as a function of R&D cost. This equation is presented in Table VI.

TABLE VI

REGRESSION ANALYSIS FOR PHASE II (NO TRANSFORMATION), FORCED THROUGH ORIGIN

Functional Relationship	r.c. Test t_{cal}	r	r Test t_{cal}	Degree of Freedom	Table $t_{0.90}$	Null Hypothesis
R& D Time = 0.20 (R& D Cost)	6.87	0.76	6.82	34	1.69	Reject

The null hypothesis associated with the regression coefficient t test is stated as follows:

H_o : The R& D cost coefficient is not significantly different from zero.

The alternate hypothesis becomes:

H_1 : The R& D cost coefficient is significantly different from zero.

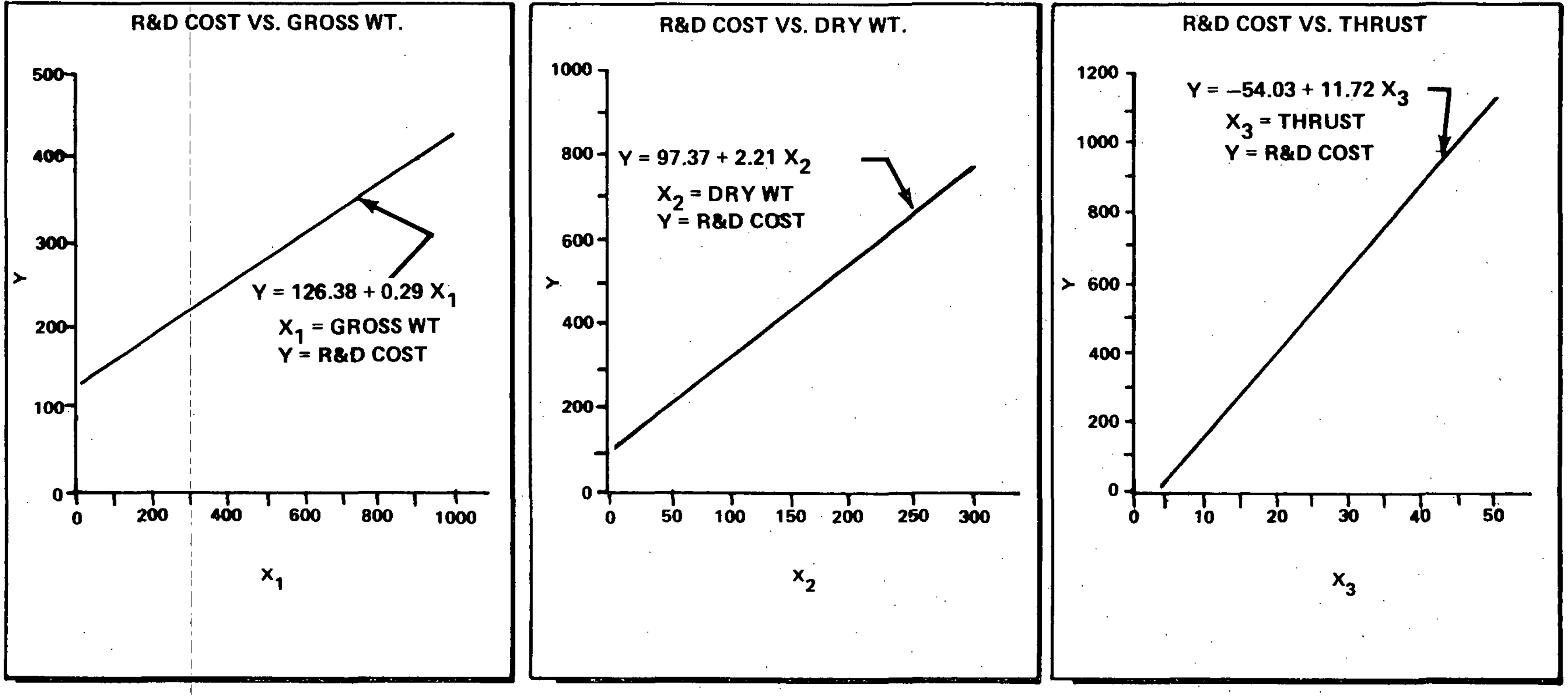


FIGURE 4. R&D COST ESTIMATING RELATIONSHIPS

The null hypothesis associated with the r test is stated as follows:

H_0 : The correlation coefficient is not significantly different from zero.

The alternate hypothesis becomes:

H_1 : The correlation coefficient is significantly different from zero.

The equation presented in Table VI has no transformation on the dependent or independent variable and is, therefore, linear in form. This equation was forced through the origin since zero time must be associated with zero cost. A graph of the functional form is shown in Figure 5.

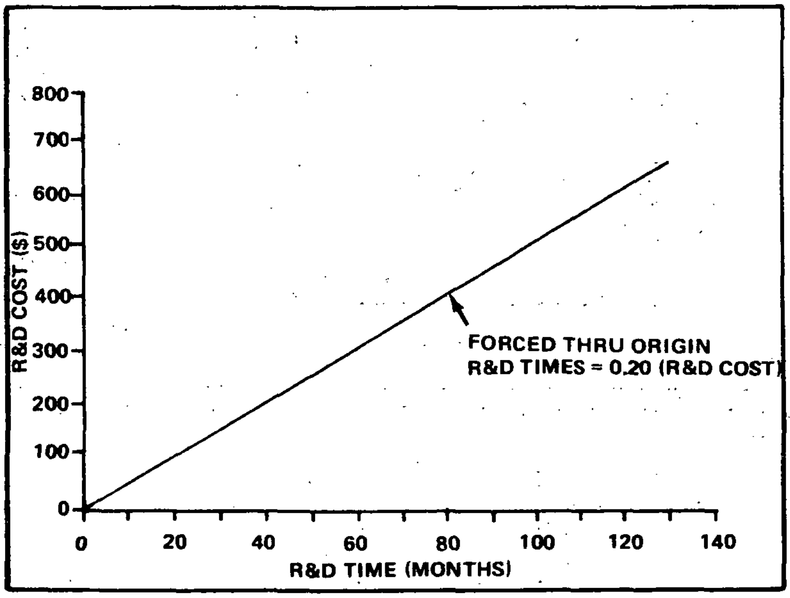


FIGURE 5. R& D COST VERSUS TIME

Phase two of the model is now complete. A functional relationship to predict R& D time based upon R& D cost is now available for use in the model.

The third phase of the predictive model was the development of the S-factors as a function of R& D time. Regression analysis was again used as the technique for determining the desired relationships. Each grouping of programs by year (A, B, C, etc.) was treated as an individual set of data to determine the correlation between R& D cost and some independent variable or variables. The following relationships were tested for each program grouping:

1. R& D cost versus gross weight
2. R& D cost versus dry weight
3. R& D cost versus thrust
4. R& D cost versus gross weight and thrust
5. R& D cost versus dry weight and thrust.

The degrees of freedom constraint (d.f. = n - p - 1, where n = number of observations and p = number of independent variables) restricted Program B and H to only one independent variable. In all the other cases except the programs in E, one of the independent variables was eliminated by the t test.

Numerous transformations were performed on the dependent and independent variables in an effort to determine the best least squares fit available. Obviously, the number of transformations available is limited only by the researcher's imagination.

In order to complete phase three of the research, some of the original 36 data points were dropped out. Subjective inspection of scatter diagrams of the programs by yearly interval, rather than all 36 programs over the entire time interval, indicated programs which appeared to fall outside the desired range of investigation when compared only to the values for a particular year. Programs A-3, E-3, and H-2 fell in this category and were eliminated. The programs grouped under I, the last year of the investigation, were also rejected based upon the required range constraints necessary to calculate the S- factor. This will be further explained in this chapter when range values are selected for the functional relationships needed to determine S-factors.

The data utilized to compute the equations of the model in this third phase of investigation are presented in Table VII. The researcher is now faced with the problem of selecting the independent variable or variables which provide the statistically best prediction equations. The regression coefficient t test was the statistical test applied where the null hypothesis may be stated as:

H_o : The coefficient of X_i is not significantly different from zero.

The alternate hypothesis becomes:

H_1 : The coefficient of X_i is significantly different from zero.

The regression analysis final results are presented in Table VIII along with the statistical calculations performed on the data. No transformation or the logarithmic transformation or a combination thereof produced the

TABLE VII

PROGRAM DATA

Program	Gross Weight X_1 (K lb)	Dry Weight X_2 (K lb)	Thrust X_3 (K lb)	R& D Cost (M $)
A-1	108.23	10.72	18.38	141.13
A-2	111.00	8.99	18.58	143.29
A-4	51.70	28.50	17.10	40.40
A-5	34.50	24.00	24.50	87.40
A-6	127.20	60.00	18.00	178.10
A-7	10.17	6.97	2.95	30.80
B-1	91.50	44.00	37.00	267.20
B-2	170.00	22.00	24.00	98.40
B-3	38.00	12.00	5.70	29.10
C-1	450.00	177.80	10.50	251.40
C-2	22.00	8.40	7.80	96.30
C-3	155.00	72.89	16.20	150.10
C-4	80.00	49.41	34.00	42.10
D-1	34.63	3.63	11.24	71.02
D-2	706.60	321.00	41.10	444.00
D-3	266.00	134.20	21.00	220.00
D-4	34.83	21.00	11.70	46.30
E-1	981.99	85.29	47.63	533.10
E-2	1015.84	102.50	48.33	544.10
E-4	31.30	13.00	50.00	87.60
E-5	24.80	12.78	14.80	33.00
E-6	6.57	4.06	1.84	21.10
F-1	114.47	12.70	18.83	145.97
F-2	255.90	23.35	26.65	237.05
F-3	226.00	16.60	25.26	219.95
F-4	11.76	7.41	3.85	21.50
H-1	49.64	24.70	20.28	361.80
H-3	28.20	16.00	16.00	46.74
H-4	51.00	25.37	15.00	409.60

TABLE VIII

REGRESSION ANALYSIS FINAL RESULTS FOR S-FACTOR CALCULATIONS

Program Grouping	Functional Relationships	r.c. Test t_{cal}	r	r Test t_{cal}	Degrees of Freedom	Table $t_{0.90}$	Null Hypothesis
A	R& D Cost $= -108.61 + 52.93 \ln (X_1)$	3.30	0.86	3.37	4	2.13	Reject
B	R& D Cost $= -62.88 + 7.48X_2$	42.49	0.99	7.02	1	6.31	Reject
C	R& D Cost $= 59.26 + 0.43X_1$	3.15	0.91	3.10	2	2.92	Reject
D	ln(R& D Cost) $= 1.65 + 0.67 \ln (X_1)$	8.14	0.98	6.96	2	2.92	Reject
E	R& D Cost $= 10.60 + 0.47X_1 + 1.21X_3$	55.51 6.01	0.99	9.92	2	2.92	Reject
F	ln(R& D Cost) $= 1.15 + 0.79 \ln (X_1)$	23.66	0.99	9.92	2	2.92	Reject
H	R& D Cost $= -1046.95 + 57.23X_2$	42.54	0.99	7.02	1	6.31	Reject

statistically best predictive equations, although numerous transformations were attempted for the functional relationships. Other statistical results on these and other regression equations utilized in this investigation are presented in Appendix B.

The functional relationships have now been presented for each grouping of programs by year, and independent variable values should now be established for these functional relationships. By substituting the same mean values in each functional relationship, the cost of performing the program in each time period will be predicted. The one time period which gives the minimum program R&D cost corresponds to the time period which gives the minimum average program length. The other time intervals will require progressively larger cost values. These R&D costs will form the basis for the S-factors to be established.

Since the functional relationships utilize gross weight, dry weight, and thrust, a value for each variable must be selected. The program grouping by year (Table VII) is again referred to and the minimum and maximum values for each variable by program grouping are selected to establish the range. These values are presented in Table IX.

After the range is established on a year-by-year basis, to achieve commonality among all years, the maximum of the minimum and the minimum of the maximum are selected for each variable as identified in Table IX

TABLE IX

PROGRAM GROUPING RANGE RESULTS

Program Grouping	Gross Weight X_1 (K lb)	Dry Weight X_2 (K lb)	Thrust X_3 (K lb)
A	10.17 - 127.20	6.97 - 60.00	2.95 - 24.50
B	38.00 - 170.00	12.00 - 44.00	5.70 - 37.00
C	22.00 - 450.00	8.40 - 177.80	7.80 - 34.00
D	34.63 - 706.60	3.63 - 321.00	11.24 - 41.10
E	6.57 - 1015.84	4.06 - 102.50	1.84 - 50.00
F	11.76 - 255.90	7.41 - 23.35	3.85 - 26.65
H	28.20 - 51.00	16.00 - 25.37	15.00 - 20.28

by the values underlined. The midpoint of the range for each variable is then selected as the independent value. These values along with their logarithms are presented in Table X.

TABLE X

MEANS OF RANGE RESULTS

Transformation	Gross Weight X_1 (K lb)	Dry Weight X_2 (K lb)	Thrust X_3 (K lb)
None	44.50	19.68	17.64
ln	3.80	2.98	2.87

Now that the independent variable values have been established, the R& D costs associated with the individual program groupings by year can be calculated. The functional relationships presented in Table VIII are the cost-estimating relationships used to predict R& D costs as a function of one or more of the independent variables (gross weight, dry weight, and thrust) presented in Table X. Program A will be used to illustrate how the R& D cost is determined from the cost-estimating relationship.

$$\text{R\&D Cost} = -108.61 + 52.93 \ln (X_1)$$

$$Y = -108.61 + (52.93)\ (3.80)$$

$$Y = \$\ 92.32\ \text{M}$$

The values for the other program groupings are calculated in a similar fashion and are tabulated in Table XI.

TABLE XI

ESTIMATED R& D COSTS BY PROGRAM GROUPING

Program Grouping	R& D Cost (M $)
A	92.32
B	84.28
C	78.32
D	67.53
E	52.87
F	62.84
H	79.20

The seven values for R&D cost can now be used to establish the S-factor. This is done through a series of ratios, each based upon the minimum program cost. The minimum cost from Table XI is obviously 52.87, the smallest value. This value is equated to unity or one for its S-factor. The method for determining the S-factor associated with the R&D cost for the first program grouping is as follows:

$$\frac{92.32}{52.87} = \frac{S}{1.00}$$

$$S = 1.75 \quad .$$

Other S-factors are established in a similar manner. The S-factors are tabulated in Table XII.

TABLE XII

ESTIMATED S-FACTORS

Program Grouping	Years from Minimum	R& D Cost (M $)	S-Factor
A	-4	92.32	1.75
B	-3	84.28	1.59
C	-2	78.32	1.48
D	-1	67.53	1.28
E	0	52.87	1.00
F	+1	62.84	1.19
H	+3	79.20	1.50

It is now possible to predict an S-factor for the G program grouping by interpolation. Assuming the S-factor relationship between the F program grouping and the H program grouping follows a linear relationship, the G program S-factor value is 1.34.

A plot of S-factors versus time is presented in Figure 6. Although a particular year has been associated with time up to this point for reference purposes, it is now possible to eliminate these years on the time scale and to assign the minimum point on the curve the value of zero. The scale is then subdivided into 1-month increments making it possible to read values of the S-factor for decompressions up to 3 years (36 months) and compressions up to 4 years (48 months). Estimates beyond this range should be evaluated with extreme caution since the range of the historical data is exceeded.

Summary

The predictive model development phase of the investigation is now complete. Functional relationships have been developed for the three phases of investigation, and the S-factors have been computed. The next chapter will illustrate the feasibility of the model which has been developed.

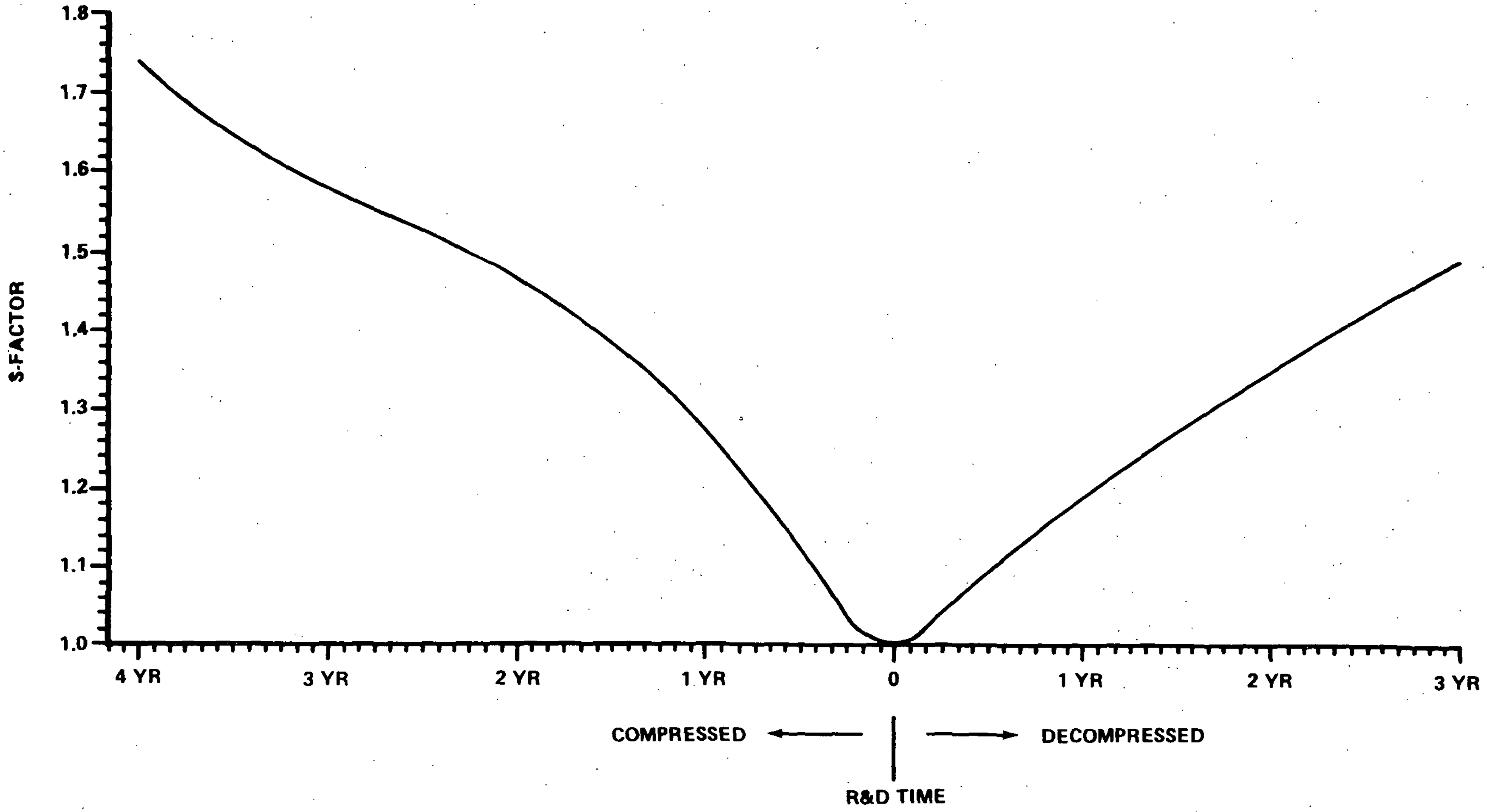


FIGURE 6. S-FACTOR VERSUS R&D TIME

CHAPTER IV

MODEL EXAMPLE AND APPLICATIONS

The predictive model development portion of this investigation used regression analysis to establish functional relationships so that S-factors to estimate the cost impact of schedule perturbations could be established. An example will now be presented to illustrate the possible use of the concept described in this research.

Example Approach

The intended purpose of this investigation was to illustrate the concept of a predictive model to provide management a new tool for gross estimations of the impact of schedule perturbations as related to cost. In order to show that the model has value as a management tool, the researcher must be able to illustrate through the use of a test case the application of the model. The model was developed in three phases; however, if the R& D cost and the R& D time are known beforehand, the first and second phases of the model can be disregarded, and one can proceed directly to the S-factor prediction curve.

Limitations of range are imposed upon the hypothetical test case from the data itself. Predicting values of a dependent variable for a given independent variable value is hazardous if the experimenter attempts such a procedure for an independent variable value outside the range of the chosen values utilized in obtaining the sample regression line. That is, extrapolation beyond the observed range of the independent variables is very risky unless we are reasonably certain that the same regression function does exist over a wider range than we have in our sample [10]. The range limits imposed upon the independent variables of this test case are as follows:

X_1: 6.57 to 1015.84 (K lb)
X_2: 3.63 to 321.00 (K lb)
X_3: 1.84 to 50.00 (K lb)

Testing the Model

Discretion must be exercised when testing the three phases of the model. This holds particularly true on the first phase, determining the R&D cost for the program. Functional relationships were presented for computing R&D cost as a function of either gross weight, dry weight, or thrust. Any one of these independent variables used separately would likely yield different R&D cost values. This necessitates the judgment factor of the experienced cost estimator in determining the optimum independent variable for a particular program. For the purpose of illustration, a hypothetical test case will be presented using only gross weight.

Any attempt at testing the applicability of the developed model must begin with empirical data in the same fashion as that utilized for the developed model. The test case used to illustrate the model has been designated Test A. The empirical data to be used for the test have been coded in the same fashion as the total model data. The test case has the following information available:

X_1: 600.00 K lb

Desired schedule evaluation: 15 months of decompression

: 15 months of compression

The first phase of testing the model involves the determination of R& D cost as a function of the independent variable gross weight. This functional relationship contains both dependent and independent variables with no transformations. The equation for this portion of the model follows:

$$\text{R\&D Cost} = 126.38 + 0.29X_1$$

$$\text{R\&D Cost} = \$\,300.38\ \text{M} \quad .$$

The R& D cost of $ 300.38 M is now available to be used in the second phase of the model which involves the determination of R& D time as a function of the independent variable R& D cost. The functional relationship contains both dependent and independent variables with no transformations. The equation for this portion of the model which has the equation forced through the origin follows:

R&D Time = 0.20 (R&D cost)

R&D Time = 60.08 months.

The R&D time which has been rounded back to 60 months is now available for use in the third phase of the model which involves the actual determination of the S-factor. As discussed previously, since the S-factor has been derived as a management prediction tool in the cost area, the manager or cost estimator could have gone directly to this phase of the investigation if sufficient empirical data were available through other means.

The R&D cost has now been established to be $ 300.38 M for a program with an R&D time of 60 months. With these parameters available the third and final phase of the model can now be implemented to predict the impact of a 15-month decompression on the Test A case. The graph of S-factor versus time is shown again in Figure 7. The 60 months which were originally scheduled for the program is placed on year zero. For a decompression of 15 months the investigator must move to the right on the time scale 15 increments. Reading up to the curve and across to the S-factor scale the S-factor is determined to be 1.24. This in turn would give:

R&D Cost = (1.24) (300.38)

R&D Cost = $ 372.47 M.

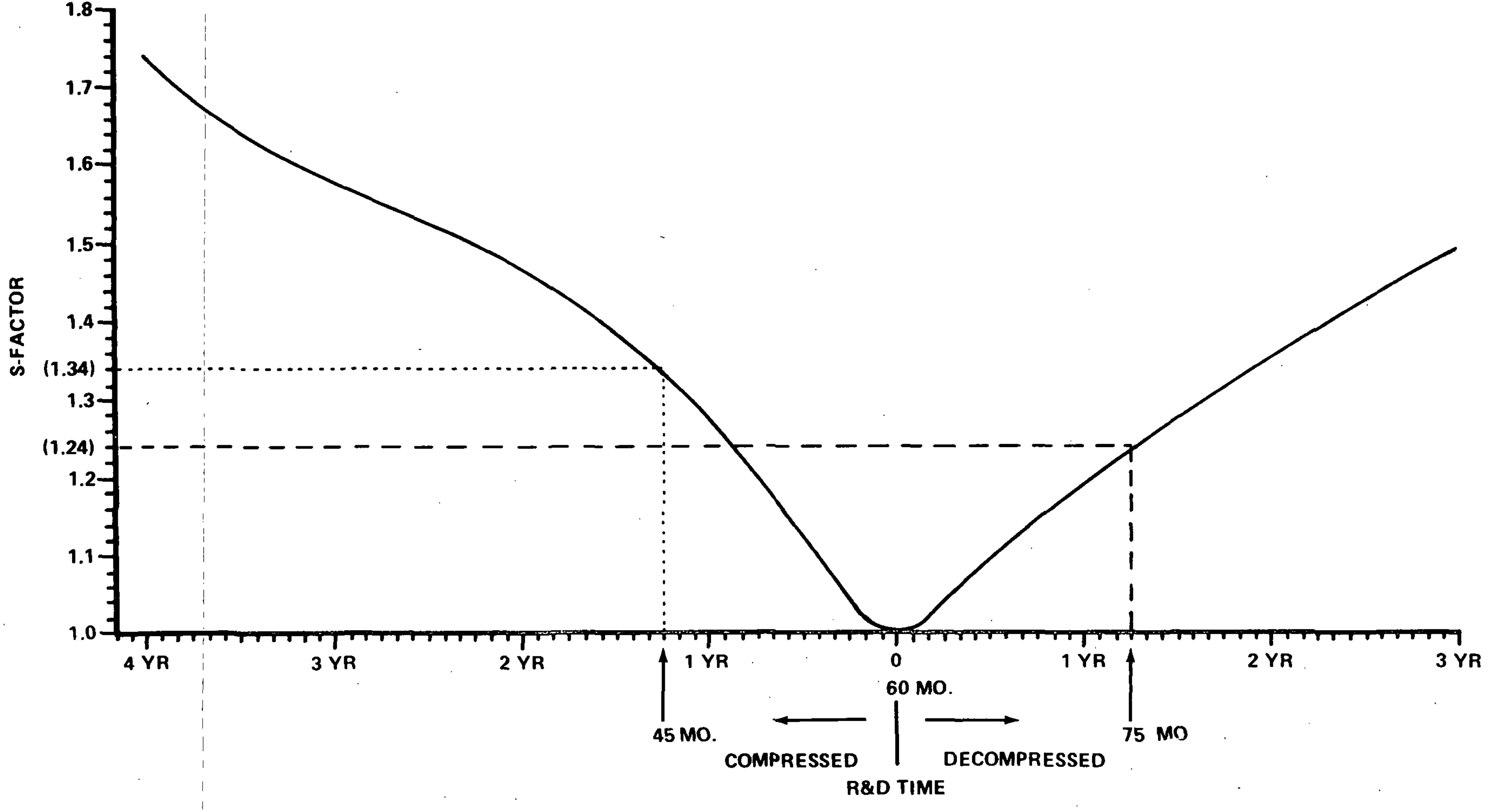


FIGURE 7. EXAMPLES OF S-FACTOR VERSUS R& D TIME

The cost model has predicted that the cost to increase a 60 month R& D program costing \$ 300.38 M to a 75-month (15-month increase) R& D program would cost an additional \$ 72.09 M.

Using the same program to compress the schedule by 15 months results in the following:

$$\text{R\&D Cost} + (1.34)(300.38)$$

$$\text{R\&D Cost} = \$\,402.51\ \text{M}.$$

In this case the cost model has predicted that the cost to decrease a 60-month R& D program costing \$ 300.38 M to a 45-month (15-month decrease) R& D program would cost an additional \$ 102.13 M.

The logic behind increased R& D costs for schedule perturbations is evident when manpower and facilities are considered. During a decompressed schedule, work is spread over a longer period of time; consequently, workers and the facilities are not utilized fully. Likewise for a compressed schedule, work is compressed into a shorter period of time, creating a demand for more workers and facilities.

Summary

The application of the regression analysis model for estimating the R& D cost impact of schedule compressions or decompressions on R& D programs has been demonstrated for a hypothetical test case. It must, however, be remembered that the cost model was developed with the intention of illustrating the concept rather than presenting the findings as fact. As more cost information is made available, the model should be updated. Care must be exercised to assure that the best data possible are being utilized. It is only then that the developed model can function as a predictive device and provide results which are meaningful.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

It has been demonstrated through this research that a cost model for determining the impact of schedule perturbations on R& D cost can be developed using regression analysis. The objectives of the investigation have been satisfied and an example has been presented to illustrate the phases of the model. A researcher should be able to use this model as an example along with "pure" data, when available, to produce another model such that when used, together with management experience and judgment, could result in more meaningful cost estimates.

Remarks and Conclusions

The ability for a cost estimator to be able to assess the impact of schedule perturbations down to 1-month duration is highly desirable. This investigation has resulted in a model that has statistical acceptance and is easily manipulated. The model also has inherent the ability to be easily updated as new information is made available. As mentioned before, a search of the literature indicates that although desirable, little work has been done concerning predictors of schedule perturbation impact on cost. This investigation has formulated this problem in terms of a simple graph.

The research has, through the use of functional relationships, produced a three-phase model. Although the third phase of the model, or the development of the S-factors versus time, was the primary objective of the model, two other phases of the model, each based upon 36 data points, are of significance as predictive models. Phase one contains a predictive model for determining R& D program cost as a function of gross weight, dry weight, or thrust. Phase two contains a predictive model for determining R& D program time as a function of R& D cost alone. These two phases, however, are independent of the third phase, the S-factor prediction phase, making it possible to move directly to phase three if sufficient information is available.

It is believed that this overall model has two important qualities which models should possess, namely, practicality and ease of implementation. The restrictions and conditions of the model are not stringent as to make the model impractical and the model can be readily understood and implemented. Although numerous calculations are involved to actually produce the model, the calculations are such that with the aid of an electronic computer the model can be easily updated. The predictive model requires only basic mathematical operations and the ability to interpolate from a graph. It is hoped that, as originally intended, the reader will now be able to formulate a model using the method described herein.

Proposals for Future Investigations

The model developed through this investigation considers only one phase of a program, the R& D portion. Further investigation might well be oriented toward the investment and operations phase or toward the total program. The difficulty with the investment and operations phase is, of course, the number of production units required.

With the progression of time, if man continues to build and launch new spacecraft, additional data from R& D launch vehicle programs will be made available. These additional empirical data along with the data provided in this model should provide the basis for a new model. The addition of new data would undoubtedly require that the entire procedure as presented be retraced since additional data would require other transformations to achieve acceptable statistical test results. The new model development could be similar to that outlined in this investigation. The benefits to be derived from an updated model would more than offset the effort required. The ability to estimate costs with a high degree of accuracy often means the difference between sound estimates and mere guesses.

As data and information on past, current, and future programs are collected through the use of computer data banks, more and more data are available to researchers. The development of sophisticated computer programs, which are easily implemented and provide rapid solution to complex problems, also serves as a tool for the researcher. Together, the data and the computer serve to provide relief to the management decision-makers as the complexities of the world increase.

APPENDIX A

MULTIPLE REGRESSION ANALYSIS FORTRAN PROGRAM FOR THE UNIVAC 1108

The mathematical procedure used in the program is the standard correlation method. Although the equations finally solved by the program are linear, many transcendental functions may be included. This is accomplished by transforming the data originally fed into the computer.

The program gives a least squares fit of an unlimited number of observations to equations of up to 30 terms, 9 of which may be dependent in a single run. Up to 30 transformations may be made upon the variables to form nonlinear terms. The terms are then handled as variables. Included also are many of the common statistical tests on the results. There are options to force the curve through the origin and to delete variables having an insignificant t value.

After the deletion of the insignificant variable — variables having an absolute value of t less than the critical value in the table — the regression is recomputed to give coefficients for the new equation.

The user of the program is urged to review standard texts on the subject of regression analysis for the mathematical derivations and limitations of this technique and to test the results carefully before using them.

The user must also bear in mind that the statistical relationships are no more accurate than the data used to form them. In order to be of value, the regression techniques must be coordinated with geometric analysis and experience. Extrapolation can only be used when there is considerable knowledge of the validity of the equation form.

APPENDIX B

TABULATION OF STATISTICAL TESTS PERFORMED BY THE MULTIPLE REGRESSION ANALYSIS PROGRAM

TABLE B-1

LAUNCH VEHICLE TO AIRCRAFT

	$X_3 = f(X_1)$	R& D Cost = $f(X_1)$
Total Variation	15.80	23.25
Standard Deviation of Y from Mean	0.83	1.01
Variation Caused by Regression	6.62	12.90
Coefficient of Determination R^2	0.42	0.56
Multiple Correlation Coefficient r	0.65	0.75
Degrees of Freedom	22.00	22.00
Variance (Total Variance-Variance by Regression)/ degree of freedom	0.42	0.47
Standard Error of Estimate or Standard Deviation	0.65	0.69
Standard Deviation of Regression Coefficient	0.11	0.12

TABLE B-2

PHASE 1

	R& D Cost = f (X_1)	R& D Cost = f (X_2)	R& D Cost = f (X_3)
Total Variation	2, 188, 641.00	2, 188, 641.00	2, 188, 641.00
Standard Deviation of Y from Mean	250.07	250.07	250.07
Variation Caused by Regression	1, 853, 875.00	1, 061, 666.00	1, 530, 962.00
Coefficient of Determination R^2	0.85	0.49	0.70
Multiple Correlation Coefficient r	0.92	0.70	0.84
Degrees of Freedom	34.00	34.00	34.00
Variance (Total Variance-Variance by Regression)/ Degrees of Freedom	9, 846.00	33, 146.00	19, 343.00
Standard Error of Estimate or Standard Deviation	99.23	182.06	139.08
Standard Deviation of Regression Coefficient	0.02	0.39	1.32

TABLE B-3

PHASE 2

	Time = f (R& D Cost)
Total Variation	290, 541.00
Standard Deviation of Y from Mean	91.11
Variation Caused by Regression	166, 837.00
Coefficient of Determination R^2	0.57
Multiple Correlation Coefficient r	0.76
Degrees of Freedom	35.00
Variance (Total Variance-Variance by Regression)/ Degrees of Freedom	3, 534.41
Standard Error of Estimate or Standard Deviation	59.45
Standard Deviation of Regression Coefficient	0.03

TABLE B-4

PHASE 3

	R& D Cost = f (X_1)	R& D Cost = f (X_2)	R& D Cost = f (X_1)	R& D Cost = f(X_1)	R& D Cost = f$(X_1$ & $X_3)$	R& D Cost = f (X_1)	R& D Cost = f(X_2)
Total Variation	18, 090.00	29, 996.00	23, 905.00	3.00	292, 305.00	3.00	77, 756.00
Standard Deviation of Y from Mean	60.15	122.47	89.37	1.04	270.33	1.13	197.18
Variation Caused by Regression	13, 237.00	29, 979.00	19, 900.00	3.00	292, 207.00	3.00	77, 713.00
Coefficient of Determination R^2	0.73	0.99	0.83	0.97	0.99	0.99	0.99
Multiple Correlation Coefficient r	0.86	0.99	0.91	0.99	0.99	0.99	0.99
Degrees of Freedom	4	1	2	2	2	2	1
Variance (Total Variance-Variance by Regression)/ Degrees of Freedom	1, 213.00	16.00	2, 003.00	0.05	49.00	0.01	42.00
Standard Error of Estimate or Standard Deviation	34.83	4.08	44.75	0.22	7.01	0.08	6.55
Standard Deviation of Regression Coefficient	16.03	0.18	0.14	0.08	0.01 0.20	0.03	1.35

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APPROVAL

A MODEL FOR ESTIMATING THE COST IMPACT OF SCHEDULE PERTURBATIONS ON AEROSPACE RESEARCH AND DEVELOPMENT PROGRAMS

By Donald F. Bishop

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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A SYSTEMS APPROACH TO THE MANAGEMENT OF LARGE PROJECTS

REVIEW OF NASA EXPERIENCE WITH SOCIETAL IMPLICATIONS

MICHAEL J. VACCARO

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A SYSTEMS APPROACH TO THE MANAGEMENT OF LARGE PROJECTS

Review of NASA Experience with Societal Implications

Dr. Michael J. Vaccaro
NASA - Goddard Space Flight Center

The reality of men having landed repeatedly on the moon is evidence of the great technological and management accomplishments of the American space program. These feats were achieved in an amazingly short span of time. When President Kennedy announced in 1961 that the United States would land a man on the moon by 1970, it seemed that this goal could hardly be realized by the end of the century, much less the end of the decade. The complexity, the risk, and the unknown factors were of such great proportion that persons in government, education, the press, and other walks of life had serious doubts about the realism of the task. Even as late as 1968, only a year before the lunar landing, the probability of success was discounted by many critics.

Why did NASA have confidence in its ability to go to the moon? Two factors accounted for its optimism: (1) the excellent technical record of the agency; and (2) the power and versatility of its systems management approach. NASA's technological success was witnessed by millions of people all over the world who viewed the lunar landings on television. NASA's use of the systems management approach to achieve its goals focused managerial attention on the applicability of this approach to reach objectives in other fields. This article explores that possibility.

THE CHALLENGE

NASA had been in existence for only three years when the Apollo project was begun in 1961. The challenge given to the agency was unparalleled in the history of government. National prestige was laid on the line in a most dramatic and awesome manner, with the entire world judging the merits of the technological and managerial prowess of the United States.

The agency of government entrusted with this seemingly impossible task was new. It was a small civilian organization endowed with no sweeping emergency powers, and required by law to operate within strict government regulations binding all regular units of the government. The nation was at peace. Financial support for the lunar landing would have to be obtained in competition with other national priorities.

NASA needed a management approach capable of nurturing technological progress while at the same time being powerful enough to ensure the coordination of many diverse organizations, resources, and skills. The agency realized that there would be many unknown hazards for men and spacecraft in the attempt to reach the moon. Therefore, the management approach had to have a capability to detect and identify potential problems and hazards in the most minute detail. Concurrently, management in the space program had to be able to move boldly and make choices decisively. Management had to be flexible and responsive to changing circumstances and new developments. To anticipate problems, the management had to be able to monitor all significant activities, test the environment for changing conditions, and obtain feedback.

Finally, because the task was of such huge proportions, it was clear that the nation's industrial and educational capacity would be involved to a large extent. Mastering space would also require an interdisciplinary approach with scientists, engineers, and professionals in scores of specialties working together in newly formed, integrated teams. Management had to have the capability to ensure that many sectors of society and professional disciplines would work smoothly toward the common objective.

NASA MANAGEMENT OUTLOOK – 1961

STAKES	POLICY	LIMITATIONS
NATIONAL COMMITMENT	CIVILIAN AGENCY	1970 DEADLINE
INTERNATIONAL PRESTIGE	WIDE USE OF INDUSTRY AND UNIVERSITIES	NO EMERGENCY POWERS
TECHNICAL LEADERSHIP		COMPETITION FOR SUPPORT

Thus the basic conditions under which NASA had to manage were:

(1) The greatest technological achievement in history was the goal.

(2) The national prestige of the United States was at stake.

(3) The goal had to be achieved within nine years – by all criteria a very short time.

(4) The goal had to be accomplished by a small, civilian agency during peace time; no emergency powers could be used; and funds would have to be obtained from Congress in competition with other needs.

(5) Major segments of industry and educational institutions in the nation would be involved in the effort, along with hundreds of professional specialties.

(6) Coordination and direction of diverse organizations, resources, and skills on a tremendous scale would be required.

(7) Precision, detailed control, and early detection of emerging problems were vital.

(8) Flexibility and a capacity to make bold and decisive choices were needed.

(9) The agency could not afford to fail.

Clearly, a wide array of innovative management methods and techniques would be needed to meet the challenge. Recent experience had demonstrated that the conduct of large scale technological projects is facilitated by the use of the systems management approach. Essential elements of this concept had been used both in large scale commercial and industrial construction projects funded by the private sector as well as R & D technology-based public service support programs funded by the Federal Government.

Basically, systems management requires that those in charge adopt as large a view of the project or problem as is practical. All significant elements must be considered by management, and a plan of action devised for integrating all personnel and resources into a unified effort to realize the objective.

INFLUENCE OF NASA ENVIRONMENT

The way in which systems management was used in NASA was heavily influenced by the background and traditions of the agency and the special circumstances involved in its evolution. Although NASA was a new agency, it was made up largely of personnel from a number of other federal research and development organizations with the following characteristics:

(1) Proud records of scientific and engineering accomplishments

(2) Highly career oriented

(3) A tradition of close cooperation with industry and universities

(4) A history of utilizing the latest technological innovations for both technical and management problems.

EMPHASIS OF MANAGEMENT APPROACH

Shaped by these considerations, NASA's adaptation of systems management had the following basic elements:

(1) Emphasis on achieving technical excellence
(2) Top management involvement in planning and implementation
(3) Strong in-house technical competence
(4) Project management
(5) In-depth monitoring of contractors.

EMPHASIS ON TECHNICAL EXCELLENCE

Success for Apollo and other major space projects depended primarily on technical capability. No matter how much money or other resources were invested, no matter how able the management team, no matter how strong the national will, success would be elusive unless the technical problems were conquered. Going to the moon was primarily a technical task. NASA Management, if it did nothing else, had to ensure that the best technical personnel available were utilized and that they were given the resources, tools, and environment to perform. The top management team, therefore, included technical experts universally recognized as leaders in science and engineering. Sensitivity to the needs of technical personnel was built in by the make-up of the management team, and by giving technical personnel high status and wide decision-making powers in all levels and phases of agency operations.

TOP MANAGEMENT INVOLVEMENT IN PLANNING AND IMPLEMENTATION

It was clear to NASA leadership that the planning process, dealing with commitments of resources and establishment of policy approaches, was crucial to the success of the lunar landing. Implementation of plans can only be left safely to experts when the process of execution has become more or less routine. This was hardly the case with the initial flights to the moon. Top management involvement in these functions was viewed, therefore, as essential.

IN-HOUSE TECHNICAL COMPETENCE

NASA realized that to most effectively utilize the technical capabilities of the industrial and university community, it was necessary to maintain a strong in-house technical competence. This basic decision, reinforced by experience from the pre-NASA agencies, was made more relevant because 90 per cent of all NASA effort was to be contracted out to industry and universities. (See Figure 1.)

PROJECT ORGANIZATION AND MANAGEMENT

In its implementation of the systems management concept, NASA utilized the Project as the central element in its organizational structure. Project organization and management are uniquely designed to harness the enterprise of all facets of the agency which can contribute to goal achievement. Yet, the project is established only to meet a single goal. When the goal is realized, it is disbanded. It can expand to nearly any size and then shrink to zero. Meanwhile, the host organization continues to conduct business in the usual manner: its essential functions continue undisturbed by the stresses and turmoil of the demands of a given project and remain ready to deal with the continuing challenges of the agency.

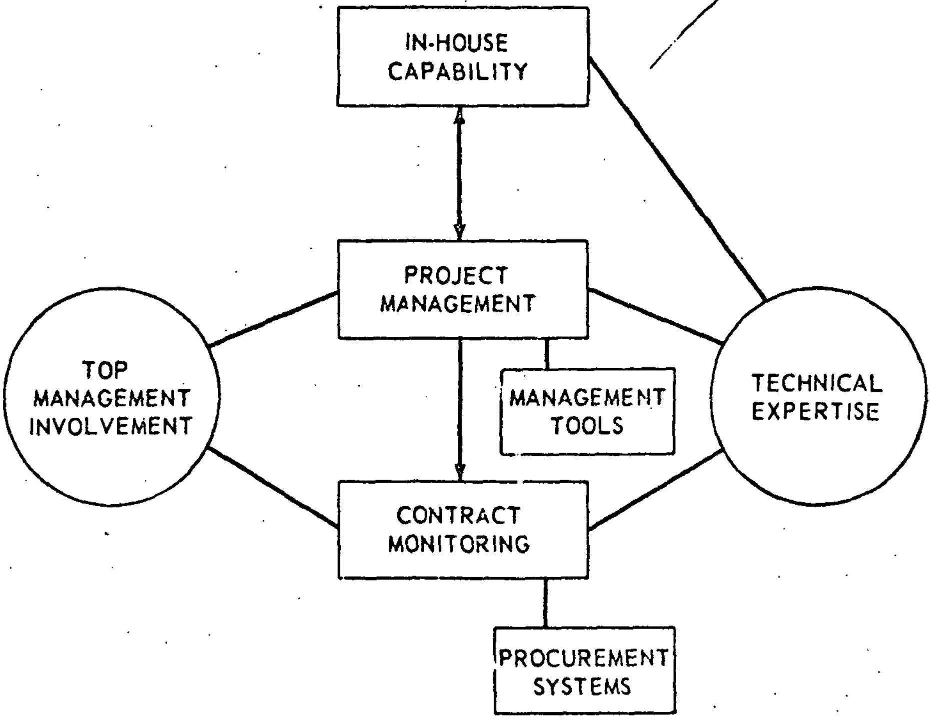

Figure 1. Systems Management in NASA

The project manager in NASA is responsible for all activities in the project, and must meet established objectives within given time and cost limits. Project managers take responsibility for organization, planning, decision-making, and follow-up. To achieve results, the project manager must utilize his technical leadership and management skills. He must possess the ability to motivate the project staff and to integrate the effort of project staff specialists with "outside" specialists.

IN-DEPTH MONITORING OF CONTRACTORS

The high risk factor of space exploration and the emphasis on success prompted NASA to insist that contractor performance be superior in all respects.

In-depth monitoring by NASA of all significant phases of contractor activity was the solution. Not only were problems averted by this knowledgeable penetration, but superior performance within time and cost limits was more frequently achieved.

APPLICATIONS TO SOCIO-ECONOMIC PROJECTS

Although the use of systems management was successful in meeting the challenges of the space program, there is a basic question as to its application to socio-economic projects, such as transportation, housing, and social services. The differences between technological and socio-economic projects are at the heart of this question. In socio-economic matters, the objectives are usually less well-defined than is the case for technological activities, the methodology is less well-developed, and the variables involved (interest groups, community preferences, etc.) are much more difficult to control. Yet, systems management has the capacity, as evidenced by the space program experience, to deal with complex problems with high degrees of uncertainty and numerous unexpected developments.

These considerations indicate that systems management is more applicable to technological enterprises than to socio-economic programs. Nevertheless, there is sufficient experience to demonstrate that systems management is useful also to socio-economic enterprises. Figure 2 represents schematically the potential for useful application of the systems approach to such ventures.

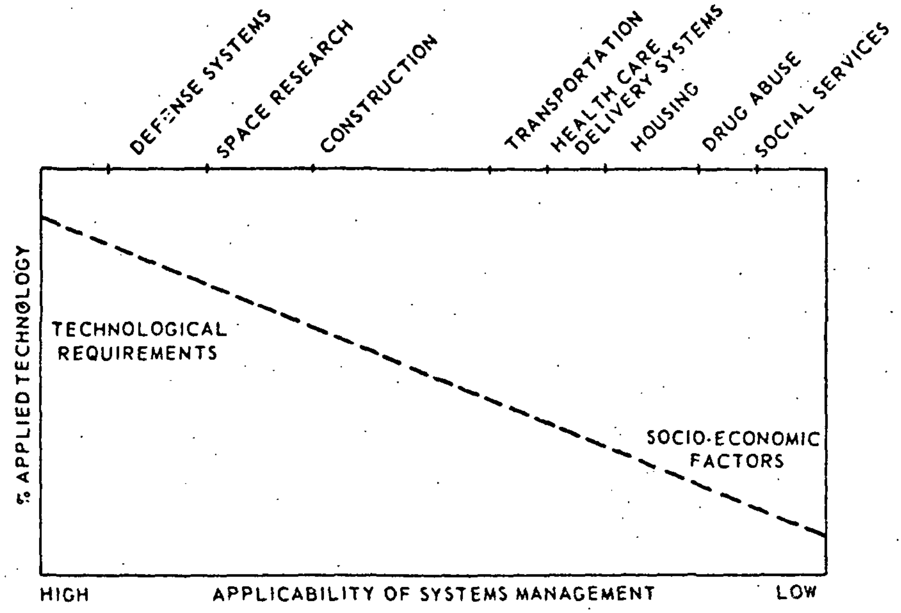

Figure 2. Systems Approach Utility Scale

In the examples that follow, the concepts of the systems management approach will be examined in connection with their application to certain socio-economic projects.

Development of a New Community

Systems management was utilized to plan and develop a new city in the United States (projected population approximately 100,000). Experts in city planning and urban living have called it an ideal place to live and work. Both employment and recreation are easily accessible to residents by foot or excellent public transportation, thus reducing much of the friction and wear and tear of modern urban life. Many other advantages are present.

The conditions under which this city was begun parallel those in the Apollo project. There was a public declaration of intent, a firm timetable, and a clear goal (including the need for a return on investment). Extensive contracting was necessary. Major differences from a space project were also present, however: The multi-thousand acre site had to be purchased from numerous small owners; the interests of environmentalists had to be accommodated; building and zoning codes plus marketing requirements had to be satisfied; and a school system meeting all state educational standards had to be created.

The systems approach used by company executives included project organization and management, and the use of a computer-based development model which was constantly modified and updated when feedback indicated that changes were vital to keep the project viable and profitable.

Operation Breakthrough

Systems management also plays an important role in bringing industrialized housing to the United States. The U. S. Department of Housing and Urban Development (HUD) is conducting an experimental project called "Operation Breakthrough." The goal is to provide factory-built housing at reasonable prices on a rapid basis to help alleviate the shortage of low and middle income housing. A systems approach was chosen because of the complexity of the project which involved proposals for changes in building codes and in zoning laws in all 50 states. Industrialized housing, both single home and large apartment units, is now being assembled at nine locations throughout the U. S.

The Metroliner

In an effort to accelerate the development of high-speed rail transportation, the U. S. Department of Transportation, working closely with railroads and several large industrial firms, has developed a pilot-program, high-speed rail link between

New York City and Washington, D. C. Because of the novel problems involved, including development of new "space age" locomotives and cars, systems management was utilized. The Metroliner is now well established as a model for fast, comfortable, and efficient rail transportation.

Housing and Social Services in County Government

Providing better local government services through the use of a systems management approach was the objective of a project undertaken from 1970 to 1972 in a county government located near Philadelphia. This attempt is of particular interest because technological tasks were not involved. Rather, the problems were social, involving housing and community services. It was necessary to obtain the active support of citizens and civic groups to ensure successful completion of the tasks. Further, prior to application of systems management, all progress in delivering the housing and community services involved had been unsuccessful.

A simplified form of systems analysis was used to identify the causes for earlier failures in achieving progress in delivery of housing and community services. Reports of these efforts indicate that utilization of the systems management approach contributed substantially to project planning and implementation.

Other Applications

The use of the systems management approach to socio-economic projects is growing. New York City is making extensive use of project management. Dayton, Ohio, utilizes "task forces" to attack basic urban problems. The University of Alberta, Canada, has a new $100 million medical complex planned and designed in conjunction with TRW, Inc., using systems management.

The range of applications is important evidence of the utility of systems management for large scale or complex ventures with substantial socio-economic influences.

IMPLICATIONS FOR FUTURE PLANNING

There is considerable evidence that the systems management approach as applied by NASA can be useful in the planning and implementation of large-scale complex projects aimed at resolving some of our socio-economic problems. Complex space flight projects and large socio-economic projects have many common elements: both exist in a dynamic environment; new knowledge and technology is required for problem solving; enormous resources need to be committed and controlled; and a complex interplay of interdisciplinary skills and institutions is involved.

It has also been demonstrated that there are significant differences that characterize space flight and socio-economic projects. Large space flight projects are amenable to final and interim goal setting, but acceptable interim goals are more difficult for the participants in the solution of socio-economic problems to define.

Space flight projects functioning in essentially monolithic organizations have, with reasonable success, been able to select project managers, team members, and the specific managerial support systems to be used in project implementation. Many socio-economic problems do not have this advantage, for they exist in an environment wherein some of the participants and managerial support systems are selected by a political process which, at that point in time, may be only tangentially related to the specific needs of the project.

These are some of the implications of applying the systems management approach to socio-economic problems. They are not insurmountable but do require adjustment and innovation in their application. Even if the approach, *in toto,* is not applicable in a given situation, many of the supportive management systems will find application. When approached with realism and applied with flexibility the systems management approach can be another "giant step" for the benefit of all mankind.

A FINAL NOTE

This article has been prepared as an analytical review of the NASA experience for the general reader with a background in management, sociology, and economics. In-depth expositions of the theory and applications of system management are available in the open literature. Exhaustive analyses of the NASA experience, in many cases funded by NASA, have been conducted by teams representing universities and nonprofit organizations. For the general reader who would like to pursue the subject in more depth, a brief, annotated bibliography of generally available reference sources is listed below:

(1) J. Gordon Milleken and Edward J. Morrison,

"Management Methods from Aerospace," Harvard Business Review, March/April, 1973.

A businessman's guide to 25 specific techniques and concepts that offer commercial sector potentialities.

(2) James Webb,

Space Age Management (New York: McGraw-Hill 1968)

The challenges to NASA management and its responses are cogently presented by NASA's chief executive from 1961 to 1968.

(3) Leonard Sayles and Margaret K. Chandler,

Managing Large Systems (New York: Harper and Row, 1971)

An in-depth analysis of how NASA and other organizations manage large projects. Includes discussion of the applicability of systems management to business and social problems.

(4) Frederick I. Ordway III, Carsbie C. Adams, and Mitchell R. Sharpe,

Dividends from Space (Thomas Y. Crowell Co., N.Y., N.Y., 1971)

A catalogue of the benefits of space technology for problems on earth, including application to communications, medicine, weather prediction, mining, and agriculture.

(5) David Wilemon,

"Transferring Space Age Management Technology," The Conference Board Record, Vol. VII (October, 1970)

An incisive review of the potential and difficulties of transferring modern management techniques to industry and government.

(6) David I. Cleland and William R. King,

Systems Analysis and Project Management, (New York: McGraw-Hill, 1968)

A valuable book describing and analyzing modern management techniques and their applications.

For the European reader, the activities of INTERNET, the International Management Systems Organization, will be of considerable interest, especially the published Proceedings of the Third International Congress on Project Planning. Information on INTERNET and details about the availability of copies of the Proceedings may be obtained from:

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