A MODEL FOR PREDICTING COST TRENDS FOR R&D LAUNCH VEHICLE CONTRACTS

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A MODEL FOR PREDICTING COST TRENDS

FOR R&D LAUNCH VEHICLE

CONTRACTS

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PREFACE

The objective of this research is to develop a simplified method for predicting total project cost on major research and development projects. The government agency project manager who has the responsibility for managing contractor effort on such projects needs information on which to base resource trade-off decisions. This is true especially in the early stages of the project when the contractor's estimate of total cost is predominantly lower than the ultimate actual cost incurred.

Through multiple regression techniques, a model is developed which predicts total cost trends early in the project life-cycle. Probabilities of total costs greater or less than given amounts can also be calculated. Finally, a simple method for measuring the schedule and cost performance of the contractor is presented. This index of performance plus three other parameters are identified as variables which affect the total cost prediction of the regression model.

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PROBLEM DEFINITION

Introduction

The advent of complex, large-scale defense and space programs demands a manager who can function in an environment of technical detail, fluctuating resources, and intricate organizational mazes. It is an environment characterized by rapid technological and management advances, fast flow of enormous sums of money, and multi-disciplined teams of sophisticated scientists, engineers and managers from government, private industry, and universities. The management mode for this environment involves scheduling, funding and expenditure of dollars, handling of data, utilization of manpower — in general, the effective use of various resources expended for the specific objectives of any one of many enormous research and development (R&D) programs.

The management requirements of these newer, more complex military and space R&D programs have forced the military services, other government agencies, and private companies to adapt their organization structure to augment traditional arrangements. Pressures of technological innovations and schedule requirements have made it necessary to establish centralized management agencies whose responsibility is to integrate many diverse functional activities on a systems basis. Various terms have been used to describe these integrative management arrangements, such as systems management, program management, weapon systems management, and project management. Although these terms have varied interpretations, the common thread in their meanings is the integrative management of a specific program on a systems basis. The project management concept, by whatever name, is now accepted as a dynamic organizational philosophy which has evolved to meet the changing managerial requirements in the research, development, procurement, and utilization of large-scale military, space, and civilian programs (1).

In the government R&D situation, where millions of dollars are spent to produce a complicated defense system or a powerful space rocket system, the major portion of the actual research and development effort is usually accomplished by a contractor and sub-contractors to a government agency. This agency, through its program management capability, has the responsibility for managing the contractor's activity. A significant facet of this management responsibility is to direct the program toward accomplishing its technical objectives by influencing design, reviewing and approving design changes, and testing the product against performance parameters, etc. The other equally important facet is the responsibility for insuring that the contractor plans and controls his resources to accomplish these technical objectives within specified time and cost constraints.

It is the management of resources, especially dollars and time, that is of primary concern in this study. Attention is directed toward the flow of planning and control information from the contractor to the project manager located in the managing government agency. When the project manager is mentioned, the primary implication is the government project manager, although the contractor's project manager faces similar problems and situations in his organization.

Cleland (2) says that the project manager is the focal point for concentrating attention on the major problems of the project. This concentration forces important program considerations by an individual who has the proper perspective to integrate relative matters of cost, time, technology, and total product compatibility. This individual determines policy, resolves major issues, commits organizational resources, makes trade-offs including time, cost, and performance, and performs a multitude of other responsibilities.

In managing a project, the cost, scheduling, and technological factors must be controlled within established constraints. Control of a project requires adequate plans, suitable standards, and an information system that will enable the project to be tracked during its life cycle to supply sufficient data for comparing expected with actual performance.

Managerial controls provide the project manager with tools for determining if the organization is proceeding toward its objectives as planned.

They advise the manager of deviations and future trends and may even provide recommended corrective action or alternative courses. Control is intended to make events conform to plans and to coordinate project affairs so that the project objectives are achieved.

Planning and control are for all practical purposes inseparable — one activity implies the other. Planning is necessary to establish a baseline point of departure and certain control factors. When the feedback-control system reports that progress will apparently not meet the planned requirements, replanning to meet the objectives is necessary and must be reviewed thoroughly in the research and development set-up. Achievement of project objectives is largely dependent on the contractor's effectiveness in planning and controlling the tasks contracted to him. Since the government is ultimately responsible for assuring operationally effective systems delivered on time and within budgeted costs, it is vitally concerned with the adequacy of the contractor's planning and control function.

Various management systems have been developed to collect and present planning and control information to the project manager. Over the years, as technical systems have become larger and more complex, so have the management systems. Periodic reporting of time and cost information, a traditional government requirement, has been the focus of many of these management systems. The flow of budget and schedule data, both planned and actual, on large R&D programs has grown to astounding proportions.

The modern large-scale computer has also contributed to the development of the highly sophisticated management information and control systems presently available to the project manager. One of the most widely recognized computerized project management systems is the Program Evaluation and Review Technique (PERT) and its extension to include cost, the PERT/COST system.

The PERT/COST system is mentioned here and critically analyzed later in this study because it is a prime example of current systems which are being criticized for their difficulty, high cost of implementation, and quantity and complexity of the information they provide to the manager. These criticisms come in conjunction with an awareness of the essential and unquestioned function of management information and control systems in large R&D programs.

It is recognized that many problems associated with management systems on space and military programs can be found in the more traditional planning and control methods; that is, they are inherent in the kind of job to be done. There are, however, many complexities in the practical usefulness of management information and control systems that go far beyond the simple pattern of the techniques themselves.

This study attempts to develop a simplified and easily administered method for providing the project manager with certain contract information. This information, which can presently be provided by a PERT/COST system, for example, is essential to the project manager when making time and cost trade-offs and includes (1) a measure of performance to date against plan and (2) an early prediction of the total cost trends for the project.

Cleland (3) has carefully pointed out in his studies of project management that the sophistication of the planning and control system depends not only on the complexity of the project but also on the ability of the participants to administer it. This observation is a primary consideration in evaluation of current systems and in determination of less sophisticated methods for securing selected information for the project manager.

Present Methods

The Program Evaluation and Review Technique (PERT) is one of the most popular and widely used tools of project management. Frazer (4) describes PERT as a statistical technique, both diagnostic and prognostic, for quantifying knowledge about the uncertainties faced in completing intellectual and physical activities essential for focusing management attention on danger signals that need remedial decisions. The system aids in identification of areas of effort where trade-offs in available resources might improve capability to meet major deadlines.

PERT establishes a method of time measurement and control around a defined plan of the work flow involved in accomplishing project objectives. It operates through a graphic display of the management plan called a network made up of activities to be accomplished, milestone events, and interrelationships and work flow constraints in the project. Estimates of the anticipated time required for each of the activities are added to the network, and this information, usually analyzed by the computer, permits the manager to recognize critical paths of his plan and to control performance toward planned objectives.

A more detailed description of the PERT system is not necessary here but may be found in any one of many references (5, 6).

The PERT/COST system, an extension of PERT to include procedures for cost estimation, collection, and control, provides the framework for planning and controlling both time and costs. This natural follow-on to PERT has become a symbol of an evolution for government contracting and administration.

PERT/COST complements the basic PERT/TIME concept but requires a cost accounting system that can merge with PERT/TIME. Thus PERT/COST cannot operate separately from a PERT/TIME system although PERT/TIME has the operational capability of standing alone (7).

Both time schedules and cost expenditures are planned and controlled within a common framework called a Work Breakdown Structure. This framework is a structured breakdown from top to bottom, of the project end items and task elements or successively lower levels of deliverable and non-deliverable end items. It terminates with functionally oriented work tasks. These work tasks are represented by activities on a conventional PERT network to which activity time and cost estimates are added. As the project progresses, actual time and expenditures are summarized and compared with the original plan to determine how well performance meets the plan and how well it is anticipated to meet it in the future. This information permits the project manager to identify problem areas, plan corrective action, and evaluate past decisions. Management action at any given point is reflected in appropriate changes to the PERT/COST plan (7).

A more detailed description of the PERT/COST system, as first officially set forth by the Federal Government, is given in the DOD/NASA PERT/COST Guide (8).

The PERT/COST system provides information in both areas of interest for this study mentioned earlier; that is, a measurement of performance to date against plan and a prediction of total program cost trends. With regard to the first, performance to date, the attempt to relate dollars spent to progress achieved through the PERT/COST "Value of Work" concept is of particular interest in this research.

The term "Value of Work" is in reality an estimate of the portion of the budgeted or planned costs attributable to work completed to date (9). The "actual" Value of Work performed to date may be quite different from the portion of the budget originally planned for the accomplishment of this work. To illustrate, if 60 percent of the funds originally allocated to accomplishment of a specific objective has been spent, it does not necessarily follow that 60 percent of the work related to this specific objective has been accomplished. With 60 percent of the funds allocated, 20 percent of the related work may be complete or, on the other hand, 90 percent may have been accomplished. The

Value of Work attempts to relate the various possible combinations of time and cost accomplishment to indicate how well dollars are being spent to complete activity within schedule. The Value of Work is then compared to actual costs accumulated to date to show whether work is being performed at a cost which is greater or less than planned.

Figure 1, adapted from the DOD/NASA Guide (8), shows the following information along with the Value of Work Performed made available to the project manager in the "Cost of Work Report":

1. The budgeted costs or original planned cost to perform the work.
2. The actual costs to date.
3. The work performed to date.
4. The projection of costs to project completion, based on actual costs to date and estimates-to-complete for work not yet performed.

The Value of Work Performed is determined by the following calculation:

$$V = \left(\frac{A}{R}\right) \times C \qquad (1.1)$$

where

V = the total Value of Work Performed.

C = contract cost estimate or original planned cost for a completed or in-process work package.

A = the actual costs to date for a completed or in-process work package.

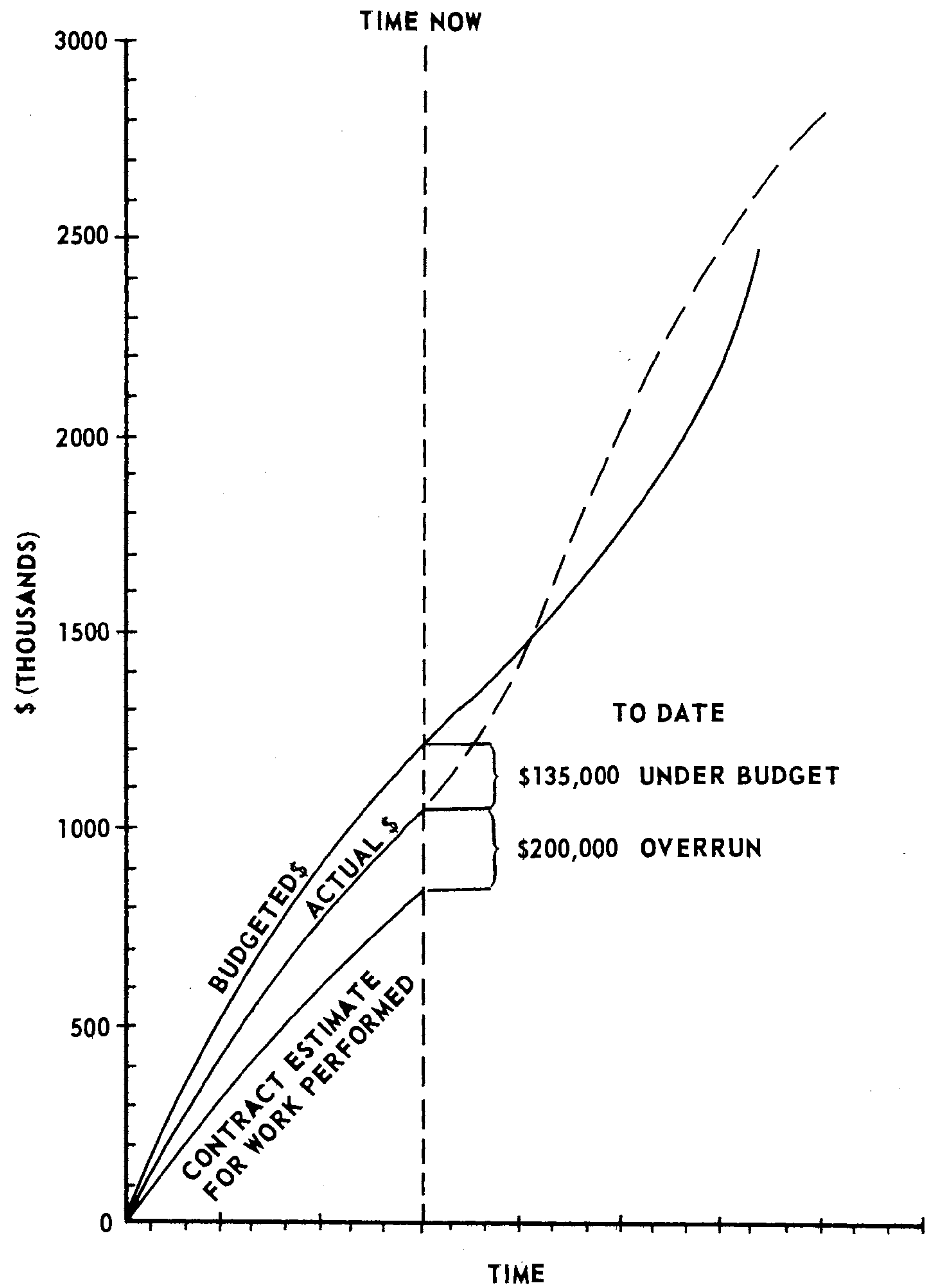

Figure 1. PERT/COST Value of Work Performed

R = the latest revised estimate for a completed or in-process work package.

For completed work packages, the latest revised estimate will be equal to the actual costs and $\frac{A}{R} = 1$. In this case, the Value of Work Performed is merely the original contract value of the work package.

For work packages in-process, $\frac{A}{R}$ is necessarily less than 1 and only a portion of the original planned cost can be credited to Value of Work Performed. This portion is estimated by the ratio $\frac{A}{R}$, representing the percentage of the total estimated cost of the work package which has already been spent. This ratio multiplied by the original contract cost gives an estimate of the percentage of the work that has actually been performed.

The example shown in Figure 1 assumes that the Value of Work Performed, calculated by the above procedure, is $800,000. The actual expenditures to date are $1,000,000, indicating that the project is $200,000 <u>over</u> the cost estimate for the work that has now been performed. This calculation is based on work that is actually completed or is in process.

Without this "value" information, the comparison of actual costs to date versus budgeted costs for work to date could be misleading. Actual expenditures are $135,000 less than what was budgeted to date. This calculation is based strictly on the time-phased cost plan and does not account for an evaluation of the <u>work</u> that has actually been accomplished.

The Value of Work Performed when compared to actual cost provides management with a good indicator of performance to date on a program through an improved method of relating dollars spent to progress achieved. The following considerations should be kept in mind, however:

1. The "value" formula, $V = \left(\frac{A}{R}\right) \times C$, assumes a linear relationship between the rate of expenditure and the percent completion. In reality, this is not so and normally the curve representing expenditures as a function of time is "S" shaped rather than linear (10).
2. The Value of Work Performed is used only as an indicator of performance to date. It is not used directly to adjust the projected or predicted cost to program completion. This estimate of total completion cost is an independent assessment based on actual costs to date plus a re-estimate of costs to completion.
3. The accuracy of the "value" estimate is dependent on the frequency of updates to the PERT/COST plan. Considering the fact that the estimate at completion, R, is a function of actual costs to date plus the revised estimate to complete, the importance of regular, realistic re-estimating of remaining work is clearly shown.

These considerations are mentioned here as a part of the development of the study hypothesis to be stated later. In conjunction with these considerations, there are also several pertinent evaluations and criticisms of the PERT/COST system in general that should be enumerated. It is important to emphasize at this point that the presentation of these criticisms of the PERT/COST system is not intended to degrade the system philosophy or to detract from the benefit that can be derived from use of the system. The intent is to use the discussion of the criticisms of the PERT/COST system as a justification for the development of a simplified technique (model) for predicting program cost trends that can be used in situations where PERT/COST is not implemented for whatever reason.

Ross (9) says that with PERT/COST, as with any budgetary attempt, the effectiveness of the effort is dependent upon a multitude of factors such as timeliness, design of the reports, knowledge of the system by the managers involved, and dependability of the budget estimates. Realistic and reliable predictions are heavily dependent on valid estimates of costs necessary to accomplish the work represented in the work breakdown structure, work packages, and networks.

Thus, the frequency of reporting, the number of reports, the validity of estimates, and even the training of appropriate personnel become essential questions to the user of PERT/COST. The government contractor ultimately must provide the answers and bear the burden of satisfying the many demands of the system including most of the data required by the system. The multitude of various demands results in heavy costs to the contractor which ultimately are passed to the government causing many to question whether the added effort to operate PERT/COST is consistent with one of the most vaunted tools of the Department of Defense itself — cost effectiveness (11).

PERT/COST is one of the costliest control systems to operate. Many managers are inclined to reject its use on this ground alone although such a view may be shortsighted. The system requires considerably more time, effort, and expense to install and operate than older, more traditional management control techniques (12). Ross (12) and Miller (13), along with others, have established the cost of operating a PERT/COST system to be in the range of one to five percent of the total project cost.

Schoderbek (14) claims that some of the problems that have arisen with PERT/COST are peculiar to defense companies, but, at any rate, they jeopardize the technique's effectiveness and the realization of its full potential. He specifically lists the following difficulties:

1. Lack of contractor support based on a reluctance to divulge internal costs and a lack of profit incentive to use PERT/COST.
2. Over-reporting of data, a tendency to generate reports management neither needs or wants.
3. Difficulty of adapting PERT/COST to the individual firm's accounting structure.
4. Timeliness of reports.
5. Invalid estimates.

The incompatibility between the PERT/COST system and the accounting structure of the contractor's firm has been an almost universal complaint. PERT/COST, not intended as a complete accounting system, relies heavily upon a sound underlying cost system to maximize the usefulness of the technique. The ability to trace significant cost overruns to their origins in order to determine the causes depends to a large extent on the basic accounting systems in use. It is unlikely that PERT/COST is feasible if it cannot be adapted to the existing accounting system and to the cost control system for "individual projects." Yet, essentially all government contractors report that they must operate dual cost control systems — one for the government's PERT/COST requirements and one for their own internal operation.

Another consideration is that the great amount of detail usually associated with PERT/COST tends to limit the effectiveness of its parent PERT/TIME system because of the restraints it places on the system's ability to respond to changes in a timely manner. This is emphasized by the fact that the networking for PERT/COST must be complete, whereas only selected elements that have an effect on schedule outcome are essential to PERT/TIME operation. All activities which generate a cost to the program must be indicated on the PERT/COST network or somehow tied to the work breakdown structure through work packages. This is necessary in order to talk about the total cost of a program as contrasted with a figure that has some unknown percentage of the program costs missing.

According to Hill (15), the following problems arise from the PERT/COST requisites for increased detail for end items:

1. Number of work orders in excess of prior cost control techniques.
2. Constant training of personnel and continual monitoring required to minimize inaccurate charging.
3. Dichotomous definitions for cost changes, especially in materials area.
4. More complexities than prior management control techniques.

To summarize, many consider the PERT/COST system to be too costly to operate. The amount of detail not only overburdens the contractor, but it increases the flow of data between contractor and government and thus adds to the project manager's dilemma of sifting out the useful and essential information. Much of the data required to operate the system is considered proprietary by the contractor and this fact naturally adds to his reluctance to cooperate with the system. The contractor is also forced, in many cases, to operate an accounting system separate from his internal one merely to satisfy the PERT/COST requirements.

Many agree that PERT/COST will be revived and refined to add a worthwhile dimension to the field of operational control (14). It is claimed, and rightly so, that the system is designed to allow the user to operate it at any level of detail desired. It is also designed to operate on a "management by exception" basis. With proper use, therefore, the range of its implementation cost can vary within wide limits. However, as the authors cited substantiate, the tendency has predominantly been to exploit the system to the point of endangering its usefulness.

Another method presently used for considering the time and cost variables of the government contract is the PERT and Cost Correlation Technique (PACCT) (16). This system was developed within the National Aeronautics and Space Administration (NASA) and was a close follow-on to similar research conducted at one of NASA's field centers (17).

The PACCT system was designed to correlate and analyze time and cost data that are already being furnished by the contractor to the government. It operates at a level where the information is normally available from other reporting media, thus requiring no additional contractor reporting. In this mode of operation, it utilizes information traditionally furnished by the contractor on government contracts and does not delve into the areas of data considered proprietary.

In addition, the PACCT system uses a computerized method for assigning costs to the activities of a network. This is in contrast to the PERT/COST system, for example, which requires a manual estimate and assignment of cost to each network activity and a constant review and update of these estimates.

Three basic steps occur in the operation of the PERT and Cost Correlation Technique. First, the original or planned costs for the project are assigned to the individual activities on the network. This step is accomplished on the computer and requires two inputs — total planned cost data by month and summary level PERT network data. (Any one of several PERT/TIME summarization programs provides this information for the latter.) Secondly, as the project progresses and the PERT network is changed and updated, the Value of Work Performed is calculated with each update. This value is compared with actual costs reported to date to give a Value Index, an indicator of contractor performance. Finally, because of time estimate changes and the subsequent increase or decrease in cost (proportional cost change assumed with time change), a new prediction of program costs is made with each update. This predicted cost is then adjusted by the Value Index to provide a PACCT forecast of total program planned cost. (Although these three basic steps will be briefly described here, more detailed discussion is available in the PACCT handbook (16).)

The first step, the assignment of budgeted or planned dollars to the original network activities, is accomplished by the following procedure within the computer:

1. Determine the total number of months of project activity for each month. (Network times are converted from weeks to months in the PACCT computer program.) This step merely adds the estimated times of all the activities expected to occur within a given month.
2. Determine the total planned cost for each month (that is, read the estimated monthly cost from a cost report.
3. Divide total cost by total number of months to obtain a rate of spending (dollars per month) for each month.
4. Multiply network activity time estimate by appropriate rate(s) to obtain total dollars assigned to activity (months × dollars per month = total dollars). This dollar amount remains with the given activity for subsequent updates and is changed only by a change in the time estimate for an activity. Any change in estimated time for the activity results in a proportionate change in its cost.

A basic calculation of PACCT is the second operational step, the Value of Work Performed to Date. Identical in philosophy to the PERT/COST term, the total Value of Work Performed is the sum of the dollars originally assigned to activities presently complete or in process. Figure 2 (16) is used to describe how these calculations are made.

As a result of the PERT/TIME summarization process and the subsequent assignment phase of PACCT, each activity has a time estimate and a cost estimate (stored in the computer) for completing the work. The cross-hatching in Figure 2 indicates completed events; thus the activities leading to event A have been completed. The original value of $38,000 for these activities is credited to the Value of Work Performed. Added to this is $2,000 for activity A-B and $2,000 for activity A-C. Since the time now is June 30 and activity A-C was completed June 2, the PACCT system assumes that four weeks of progress have been made on activity C-D (June 30 minus June 2). A proportional amount of the value of the activity is credited to the Value of Work Performed, ($4/12 \times \$6,000 = \$2,000$). The formula used here to calculate "value" for activities in process is basically the same as for PERT/COST. The calculation here is based on actual time expended compared to plan, however, whereas the PERT/COST calculation is based on actual dollars spent compared to latest revised estimates of dollars to be spent.

The total Value of Work Performed is compared with the Actual Cost reported to date to provide a Value Index which is used as an indicator of

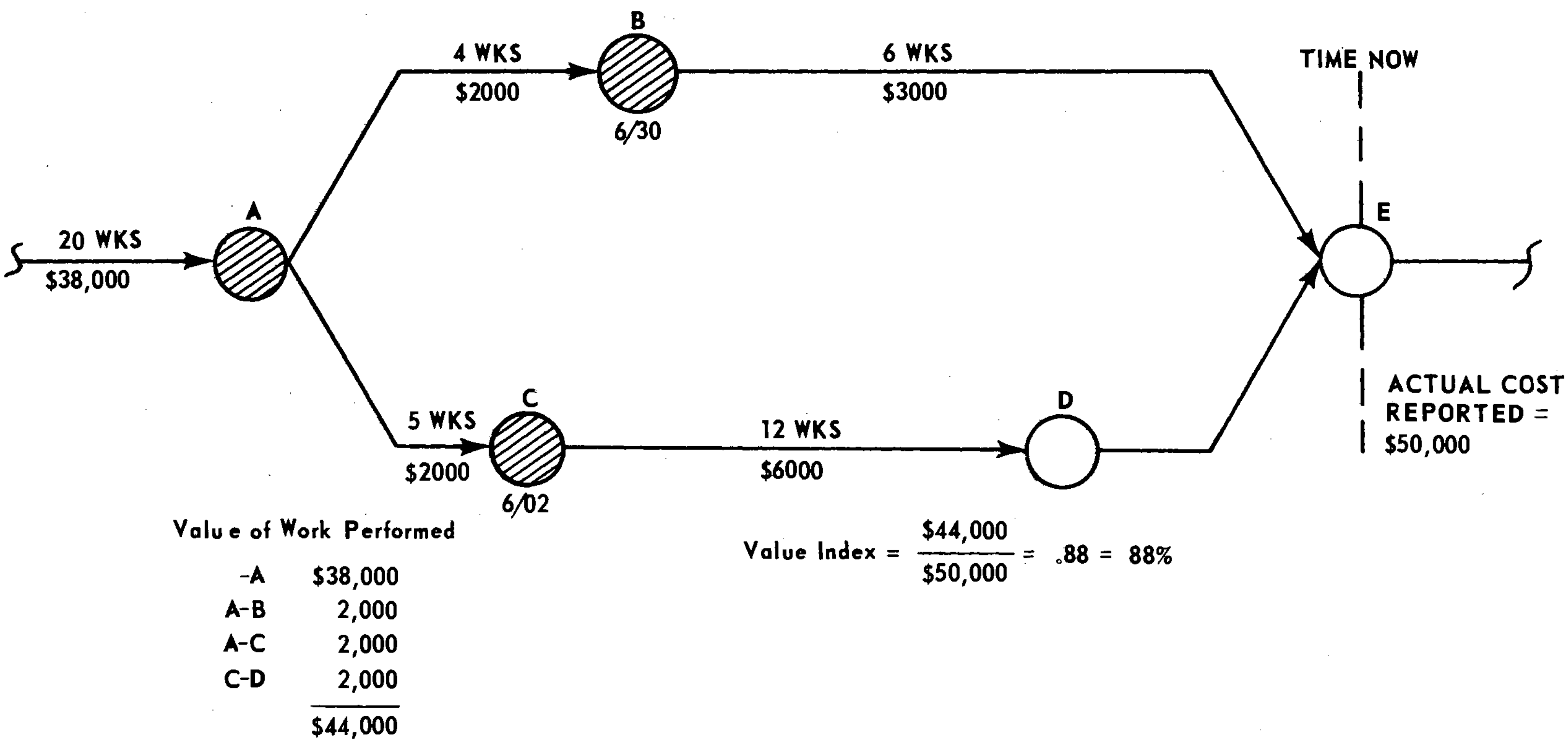

Figure 2. PACCT Value of Work Performed

contractor effectiveness. The Value Index is equal to the Value of Work Performed divided by Actual Costs:

$$V.I. = \frac{VWP}{\text{Actual Costs}} \qquad (1.2)$$

or for the example in Figure 2, \$44,000/\$50,000 = 88 percent. This index is used as an adjustment factor in predicting future program costs.

As discussed earlier, changes to the baseline PERT network will result in increases or decreases to the program dollar requirement and will force a change in the dollar allocation. A summation of the revised dollar requirements provides the predicted cost figure for the program based on the latest PERT plan.

The PERT Predicted Cost is then adjusted by the Value Index to factor past performance into future cost estimates. This adjustment is made on the assumption that a contractor's performance to date is an indicator of his future performance. Thus,

$$\text{PACCT Forecast} = \frac{\text{PERT Predicted Cost}}{\text{Value Index}} \qquad (1.3)$$

Several facets of the PACCT system have been questioned:

1. Equal weighting of all activities for cost assignments; i.e., it is assumed that either the same level of resources is required to accomplish one task as another or that the differences in levels tend to balance out as smaller activities are summarized into larger ones.

2. Assumed straight line relationship between activity time and cost estimates. All predicted costs are based on the assumption that the cost for accomplishing an activity will vary in direct proportion with the time estimated to complete the activity.

3. Tendency to average costs across monthly time periods when assigning costs to activities that span more than one month.

In addition to these assumptions, a major drawback to the use of PACCT has been the difficulty of making a valid update to the system. As with PERT/COST, a parent PERT/TIME network is essential for maintaining a PACCT system on a project. The PERT/TIME network is subject to constant change; in fact, it is well known that the network must be dynamic and constantly updated to properly show the changes in project plans. Constant change causes havoc in the PACCT system. This fact is easily understood if it is recalled that a baseline is established by assigning the project budgeted cost to the activities on the baseline network. In the computer, the cost rate thus assigned is associated with the particular activity originally shown on the baseline network. If such a baseline activity is deleted from the network, the dollars associated with the activity are lost; the computer has no way of identifying them. Even a change in the activity number has the same effect. New activities added to the system have no corresponding baseline cost rate and are therefore shown at zero cost. Manual methods for overcoming this deficiency can be employed but the validity of resulting predictions is subject to question and the amount of work involved remains a large task.

Taken as a broad, summary level indicator, the PACCT method can be of assistance to the project manager in correlating the schedule and cost data that is available to him. Its low cost of application, as compared to PERT/COST, adds to its advantages. However, the system is dependent on a PERT/TIME base which, in most cases, must be furnished by the contractor. It is based on heavy assumptions and finally, the validity and usefulness of the technique is largely hampered by the difficulty of updating the information.

A more recent philosophy for furnishing contract performance information to the project manager is the Cost/Schedule Planning and Control Specification (C/SPCS) (18). C/SPCS is not a management system, but is a set of criteria which government contractors are required to meet in their internal planning and control function so that their internal system will support efficient, effective management of schedule and cost.

Prior to development of this approach, the government imposed its requirements for contractor planning and control by specifying systems and techniques to be used by the contractor in the performance of the contract. According to the Air Force, these systems (DOD/NASA PERT/COST being a case in point) are not always compatible with planning and control systems already used by the contractor organization, and their imposition has generally resulted in maintenance of two systems, one for internal use and one for government reporting (18).

Under the C/SPCS method, the contractor is free to choose his own internal system for planning and control. The basic requirement is that he convince the government through demonstration and review that this system meets certain general criteria; the more detailed orientation and implementation of internal systems is left to the discretion of the contractor.

Briefly stated, C/SPCS requires a contractor to assign the work required to meet contract objectives to specifically identified organizational elements, to establish internal schedules and budgets for the work, and to periodically compare actual cost and schedule performance against the planned schedules and budgets. Variances resulting from these comparisons provide managers, both contractor and government, with schedule and cost performance indicators which enable them to determine program progress by the specific element of work and to identify problem areas.

The government provides the contractor with the upper level of the work breakdown structure which serves as the summary level for reporting purposes. The contractor extends this structure, consistent with the way his particular company is organized, down to the level where the work is to be done. Summarized information through this structure provides the basis for cost and schedule performance reporting to both contractor and government management. In addition to this requirement, more specific requirements dealing with documentation of the contractor's internal systems, cost of materials, methods of incorporating changes, etc., must be met by the contractor.

The basic objective of the Cost/Schedule Planning and Control Specification is to offer flexibility to a contractor in selecting systems and techniques best suited to his particular internal needs while still satisfying government requirements. At the same time, by reporting to the government only at summary levels of the work breakdown structure, the flow of information between the contractor and the government is reduced. These two far-reaching advantages are indications of the trends in contractor reporting on government contracts. The methods developed in this study, while placing no additional reporting requirements on a contractor beyond those of a scheme such as C/SPCS, permit the government project manager to use the available summary level information to measure the performance of the contractor and predict total program cost trends.

Objectives of the Study

The objective of this study is to develop a simplified method for predicting total project cost trends on a large government research and development project. This objective will be accomplished through the development of a model whose supporting factors of data (variables) are easily obtainable from summary level information normally furnished by the contractor to the government or already available to the government. One model variable of pointed interest will be a measure of the contractor's performance in meeting the schedule and cost requirements of the contract (similar to the Value Index of PERT/COST and PACCT). A predictive model and its related variables, one of which is a contractor performance index, will provide the project manager with information needed for more effective planning and control: (1) a measure of performance against plan to date and (2) a prediction of total program cost trends.

A critical analysis of present methods for providing these two elements of information to the project manager has been presented to reveal some of the difficulties of using more sophisticated systems and techniques, such as PERT/COST and the PERT and Cost Correlation Technique. The Cost/ Schedule Planning and Control Specification philosophy was examined to indicate the trend toward less sophisticated system requirements on the contractor and reduced flow of data from the contractor to the government.

The model developed will not be dependent on a PERT/TIME base as the PERT/COST and PACCT systems are. Rather, it will employ the use of summary level schedule data (milestones) available from any contractor schedule reporting scheme. As with C/SPCS, these milestones may be supported in the contractor's internal operation by a PERT/TIME system or by any other acceptable schedule and planning technique.

Variation of the contractor's monthly estimate of the total project cost from the actual total cost that is finally incurred will be the area of investigation. The objective will be to develop an adjustment factor which, when applied to the contractor's estimate of project total cost, will provide a forecast cost that varies less from the actual cost than did the contractor's estimate. This is the basic approach of the PACCT system, but must be accomplished in a manner that is much easier to establish and maintain than PACCT.

Experience with R&D contracts shows that the variance between the contractor's estimate and the actual cost is larger in the early months of a project and tends to become smaller toward the end of the project. One study of the history of estimates from 22 research and development contracts for major hardware deliveries concluded that early estimates, made near the beginning of a development program, are particularly unreliable, off many times by a factor of 2, 3, or even 10 (19).

In view of these considerations, the objectives of this study can be summarized and stated in a research hypothesis as follows: Total project cost trends for large research and development programs can be predicted early in the project life cycle; this prediction will be dependent only on summary level reporting data and will be based on the contractor's total cost prediction adjusted by one or more related parameters, such as the contractor's schedule and cost performance to date.

CHAPTER II

PROBLEM SOLUTION — METHOD I

The Approach

The desired objective of the problem solution is the development of a predictive device which can be used by the project manager on a system in the early stages of development to determine the total cost of the project. This device will be based on the contractor's estimate of the total project cost which, in most cases, is the best estimate the project manager has available to him. However, the predictive device proposed here will provide an adjustment to the contractor's estimate which should consistently result in an estimate closer to the actual cost.

In the first approach to the problem solution, a Value Index (V.I.), or measure of the contractor's performance to date, will be calculated and used as the adjustment factor to the contractor's estimate. This Value Index will be identical in concept to the one described in the PERT and Cost Correlation Technique (PACCT). However, its calculation will not be dependent on a PERT/TIME network and will therefore be greatly simplified.

In the PACCT system, budget costs are assigned to network activities, and the Value Index is a function of the original dollar amounts assigned to completed activities and activities in process. Rather than use activities as the measure, the proposed approach will use a count of events or "milestones" as the measure of schedule performance. As with the Cost/Schedule Planning and Control Specification, these milestones may be supported by or even be derived from a PERT system, but this is not necessary for their effective utilization so long as they meet basic criteria. The schedule performance indicator will be the ratio of milestones accomplished to milestones scheduled, both calculated up to any given time in the project.

The cost performance indicator will be calculated as the ratio of the originally planned (or budgeted) cost to the actual cost, again up to any given date in the project life.

Thus, these performance measures are calculated as follows:

$$\text{Schedule Index (S. I.)} = \frac{\text{Milestones Accomplished (MS-A)}}{\text{Milestones Scheduled (MS-S)}} \qquad (2.1)$$

$$\text{Cost Index (C. I.)} = \frac{\text{Planned Cost}}{\text{Actual Cost}} \qquad (2.2)$$

The Value Index will be calculated as follows:

$$\text{Value Index} = \text{(Cost Index) (Schedule Index)} \qquad (2.3)$$

These calculations are based on the following definitions:

1. Milestone — Any one of a master list of events of major significance to a project, selected by the project manager in collaboration with the government agency-level program management; it must

include events which represent major accomplishments toward the achievement of the program technical objectives.

2. Milestones Scheduled (MS-S) — The cumulative count of all milestones originally scheduled to be complete by a given date.
3. Milestones Accomplished (MS-A) — The cumulative count of all milestones completed by a given date.
4. Planned Cost (PC) — The portion of the original program budget which was planned to be expended by a given date.
5. Actual Cost (AC) — The cumulative actual cost incurred up to any given date as reported by the contractor.

It can be shown, in general terms, that the Value Index calculated as the product of the Schedule Index and the Cost Index is theoretically equivalent to the Value Index of the PACCT system. To illustrate this point, the calculation of the PACCT Value of Work Performed must first be examined. The Value of Work Performed is equal to the sum of planned dollars originally assigned to activities completed by "time now," the present. It should be recalled that the planned dollars for a total project are assigned to all activities of a summary level network on an equal basis; i.e., it is assumed that the rate of spending for any activity in a given month is the same as the rate for any other activity during that same month.

Thus, the expenditure for completed activity is summed to calculate the Value of Work Performed, which is in reality a measure of the progress made in accomplishing the activities according to the PERT schedule, but which is related in terms of the originally planned dollars rather than time. In other terms, it can be said that the VWP equals the original budget or planned dollars assigned to that portion of the network that is now completed.

In terms of milestones rather than activities, the portion of the network completed at any time is represented by the ratio of the Milestones Accomplished to the Milestones Scheduled. Thus,

$$VWP = (\text{Planned Cost})\ (\text{Portion of Network Completed}) \ ,$$

or

$$VWP = PC \ \frac{MS\text{-}A}{MS\text{-}S} \qquad (2.4)$$

The only significant difference between the Value of Work Performed calculation based on activities and that based on milestones is that the former takes into account work in process. Recall that in the PACCT system, value was given for a portion of an activity based on the ratio of the weeks of work completed to the total time estimated for the activity. The proposed milestone calculation would reserve credit for work performed until all activity leading to the event was complete. This difference is a function of the number of milestones and is not considered significant.

Calculations on a small portion of a sample network are used in Figure 3 to illustrate the above discussion.

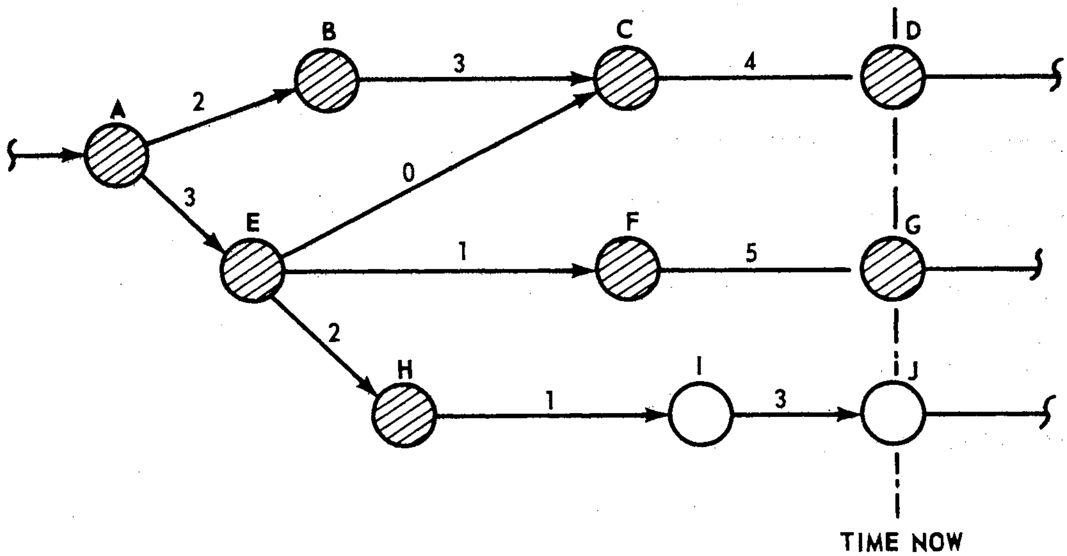

Figure 3. Value of Work Performed Calculations

Numbers between events represent planned dollars assigned to the activities by the PACCT process, and cross-hatched events indicate completion. Calculated according to the PACCT formula,

$$VWP = 2 + 3 + 4 + 3 + 0 + 1 + 5 + 2 = 20$$

Calculated according to the equivalent milestone expression, equation (2.4), this becomes

$$VWP = 24 \quad \frac{8}{10} = \frac{192}{10} = 19.2$$

where 24 is the total planned cost assigned to activity which was scheduled for completion by "time now" and $\frac{8}{10}$ represents the portion of that activity that has actually been completed.

This example, although crude, should illustrate that these two calculations of the Value of Work Performed are theoretically equivalent; any difference is created in the assignment of dollars by the PACCT system versus count of milestones, and in the fact that work in process is unaccounted for in the proposed calculation.

To now show that the calculations of the Value Index are equivalent, one must first recall that the PACCT Value Index is the ratio of Value of Work Performed to actual costs reported, or

$$V.I._{PACCT} = \frac{VWP}{AC} \tag{2.5}$$

Substituting the expression for calculating Value of Work Performed in milestone terms, equation (2.4), into equation (2.5) gives

$$V.I._{PACCT} = \frac{PC \dfrac{MS\text{-}A}{MS\text{-}S}}{AC}$$

or,

$$V.I._{PACCT} = \frac{PC}{AC} \quad \frac{MS\text{-}A}{MS\text{-}S} \tag{2.6}$$

The equivalent expression to (2.6), developed strictly from the milestone approach, will now be calculated. Expressions for the Schedule Index based on milestone count and for the Cost Index were developed in equations (2.1) and (2.2). If these expressions are substituted into equation (2.3), the expression for the proposed Value Index, it is obvious that the proposed Value Index is equivalent to equation (2.6):

$$V.I._{PROPOSED} = \frac{PC}{AC} \quad \frac{MS\text{-}A}{MS\text{-}S} \tag{2.7}$$

Acceptance of the proposed method for calculating the Value Index provides a much simplified method for establishing and maintaining this index as a measure of contractor performance. In the approach to problem solution proposed here, the Value Index so calculated will be used as the adjustment factor to be applied to the contractor's estimate of total project cost to provide the predicted total cost, or

$$\text{Predicted Cost (PRC)} = \frac{\text{Contractor's Estimate (CE)}}{\text{Value Index (V.I.)}} \tag{2.8}$$

This prediction, if proven sufficiently accurate, will satisfy the thesis of this research. It is obvious that the prediction is based on the contractor's total cost but is adjusted by a related parameter, the Value Index, an indicator of how well the contractor has performed in the past. The proposed method of prediction, based on the milestone approach to calculation of the Value Index, is dependent only on summary level data available from the normal contractor reporting scheme.

Model Assumptions

In any research study, certain assumptions must be made. For this study, the assumptions concern the use of the supporting data and the approach itself and include the following:

1. Total project cost data will be used to develop the predictive model; therefore, the resulting model is applicable to total cost data rather than to any elemental breakdown of cost such as direct, indirect, contractor fee, etc., or to any functional breakdown such as manufacturing, engineering, testing, etc. This implies that any factor calculated and used as an adjustment to the contractor's estimate of total project cost can either be assumed to apply equally to all elements of the total cost, or, with a gross predictor as proposed here, can be expected to have a balancing effect across cost elements.
2. Supporting data for the study is derived from large launch vehicle programs (15,000 to 300,000 pounds dry weight) ranging in total program cost from 100 million dollars to one billion dollars. Direct application of the resulting model must be limited to these considerations; however, use can be made of the approach described as discussed later.
3. Cost data is obtained from the Contractor Financial Management Report (NASA Form 533) and schedule data from the Saturn V Program Schedules, Status and Analysis (Marshall Space Flight Center Form 774). Both of these sources are assumed to contain accurately reported data.
4. The model is limited to cost-plus government contract arrangements but is unaffected by particular types of cost-plus arrangements.

5. A baseline for calculating the variables of the model can be established at any time during the life cycle of the contract, not necessarily at the actual initiation of the contract.

Data Collection

The data categories required for the first approach to problem solution have been described earlier. They are (1) planned cost, (2) actual cost, (3) milestones scheduled, (4) milestones accomplished, (5) contractor's estimate of total cost, and (6) actual contract total cost. All this information is available in one form or another from within the government agency. Although the data utilized is not government classified information, undue exposure is prevented by coding the data. This in no way distorts the empirical data or the results obtained in this investigation.

The required data is available in most cases for discrete periods of one month. In cases where the contractor's projected cost was recorded only for three month periods or quarters, a straight line spending rate was assumed for the three months, an assumption common with use of these figures by the government. The month in which the model is initiated or, in other words, where the measure of the variables is begun, is designated month zero, and the months are consecutively numbered from that point.

The results of the data collection effort are shown in Tables I through V. Tables I through IV record the cost data for each of the four projects considered; Table V records the schedule information for these projects over the same 42-month period.

TABLE I

PROJECT "A" COST DATA
(Thousands of Dollars)

Month	Total Planned Cost (Cumulative)	Total Actual Cost (Cumulative)	Contractor Estimate of Total Cost
1	16,976	19,985	378,761
2	33,952	39,254	381,044
3	50,928	57,580	370,041
4	66,948	75,764	372,205
5	82,969	94,652	375,073
6	98,989	114,187	356,896
7	113,363	127,751	442,589
8	127,737	144,668	445,737
9	142,113	167,045	454,344
10	156,646	189,422	463,031
11	171,180	211,799	541,682
12	185,713	219,128	568,713
13	199,220	225,219	561,715
14	212,727	228,648	571,802
15	226,234	244,653	570,256
16	229,749	254,090	564,946
17	232,724	266,440	574,177
18	235,969	280,502	572,211
19	243,842	289,634	569,142
20	251,713	300,620	542,487
21	259,984	314,874	543,010

TABLE I (Continued)

Month	Total Planned Cost (Cumulative)	Total Actual Cost (Cumulative)	Contractor Estimate of Total Cost
22	267,455	325,369	540,092
23	275,326	334,162	584,141
24	283,197	344,511	581,159
25	291,068	352,402	576,848
26	299,455	363,321	570,595
27	310,663	377,517	570,000
28	322,268	385,983	565,019
29	334,294	395,769	552,400
30	347,065	407,922	550,971
31	354,788	415,720	546,347
32	362,509	427,752	544,172
33	370,230	436,716	545,524
34	379,705	444,191	540,800
35	389,178	448,212	533,168
36	398,651	458,732	532,943
37	406,413	465,295	529,809
38	414,173	472,320	525,410
39	421,933	481,570	521,256
40	427,792	490,373	517,305
41	433,650	498,160	514,640
42	439,508	506,759	506,759

TABLE II

PROJECT "B" COST DATA
(Thousands of Dollars)

Month	Total Planned Cost (Cumulative)	Total Actual Cost (Cumulative)	Contractor Estimate of Total Cost
1	18,098	16,593	365,921
2	36,197	37,677	368,907
3	54,296	58,885	393,899
4	70,650	76,499	394,248
5	87,004	91,314	391,768
6	103,358	111,442	424,765
7	118,838	127,342	422,724
8	134,320	145,849	423,376
9	150,800	168,817	428,492
10	165,610	187,485	430,152
11	180,520	206,513	432,170
12	195,330	229,193	437,842
13	209,740	252,024	445,850
14	224,150	273,010	452,011
15	238,559	298,879	732,604
16	251,177	319,347	733,144
17	263,795	340,328	761,998
18	276,413	363,096	760,735
19	284,089	381,166	758,267
20	291,765	405,047	756,742
21	299,441	430,404	762,127

TABLE II (Continued)

Month	Total Planned Cost (Cumulative)	Total Actual Cost (Cumulative)	Contractor Estimate of Total Cost
22	307,117	446,996	757,247
23	314,793	469,609	762,719
24	322,471	488,448	765,598
25	330,147	502,420	761,863
26	337,823	522,937	764,516
27	345,499	545,508	763,586
28	353,175	561,029	763,229
29	360,851	580,943	777,299
30	368,529	598,574	775,018
31	372,577	612,662	772,408
32	376,627	634,797	823,574
33	380,677	653,623	823,429
34	384,727	669,637	821,681
35	388,777	688,573	819,654
36	392,827	703,586	806,429
37	396,877	721,666	805,207
38	400,927	737,316	804,539
39	404,980	753,241	804,450
40	409,030	767,350	803,019
41	413,080	784,552	801,131
42	417,130	801,557	801,832

TABLE III

PROJECT "C" COST DATA
(Thousands of Dollars)

Month	Total Planned Cost (Cumulative)	Total Actual Cost (Cumulative)	Contractor Estimate of Total Cost
1	11,666	13,597	218,795
2	23,333	25,199	218,731
3	35,000	36,829	314,214
4	46,111	48,511	312,367
5	57,221	64,731	315,058
6	68,332	76,653	312,066
7	78,332	87,357	325,496
8	88,332	102,203	326,956
9	98,332	113,834	383,061
10	107,332	128,709	392,346
11	116,332	140,690	390,768
12	125,332	152,151	418,668
13	132,998	168,927	390,643
14	140,664	180,932	348,582
15	148,330	193,556	349,918
16	154,663	205,797	351,474
17	161,007	221,236	332,082
18	167,340	237,379	377,420
19	171,468	248,056	336,497
20	175,596	258,697	371,038
21	179,724	267,884	370,020

TABLE III (Continued)

Month	Total Planned Cost (Cumulative)	Total Actual Cost (Cumulative)	Contractor Estimate of Total Cost
22	183,852	281,547	371,825
23	187,980	291,085	383,817
24	192,108	300,089	383,470
25	196,236	311,611	385,863
26	200,364	321,101	382,785
27	204,492	330,215	383,979
28	208,620	341,260	388,024
29	212,748	349,793	392,157
30	216,876	357,670	395,345
31	218,736	367,648	400,960
32	220,596	375,922	405,058
33	221,456	383,998	436,499
34	223,316	395,290	437,660
35	225,176	402,657	437,390
36	227,036	410,661	461,387
37	228,896	418,847	461,900
38	230,756	429,770	464,852
39	232,616	440,260	462,863
40	234,476	447,204	461,789
41	236,336	454,859	461,681
42	238,196	463,979	461,620

TABLE IV

PROJECT "D" COST DATA
(Thousands of Dollars)

Month	Total Planned Cost (Cumulative)	Total Actual Cost (Cumulative)	Contractor Estimate of Total Cost
1	980	501	60,055
2	2,766	1,363	59,131
3	4,891	2,331	57,974
4	6,624	3,489	57,399
5	8,357	4,820	56,997
6	10,091	6,373	82,238
7	12,076	7,445	81,743
8	14,060	8,619	81,174
9	16,045	10,019	93,229
10	18,479	11,721	92,890
11	20,913	14,307	93,718
12	23,348	17,390	100,319
13	25,525	17,923	104,391
14	27,702	19,713	105,241
15	29,878	23,431	106,307
16	31,726	26,573	106,276
17	33,573	30,326	116,995
18	35,420	34,087	116,707
19	37,513	37,902	116,707
20	39,606	40,849	119,876
21	41,699	44,753	119,949

TABLE IV (Continued)

Month	Total Planned Cost (Cumulative)	Total Actual Cost (Cumulative)	Contractor Estimate of Total Cost
22	43,792	48,449	120,142
23	45,885	52,533	121,647
24	47,978	59,619	122,492
25	50,071	61,383	121,715
26	52,164	64,913	121,949
27	54,257	69,615	122,666
28	56,350	72,723	123,176
29	58,443	75,961	123,242
30	60,536	79,788	123,461
31	62,254	82,531	123,461
32	63,972	86,498	128,065
33	65,690	89,987	127,758
34	67,408	93,383	127,726
35	69,126	96,444	126,533
36	70,844	101,707	127,340
37	72,562	106,938	128,581
38	74,280	109,912	128,085
39	75,998	113,752	124,837
40	77,716	117,233	125,006
41	79,434	120,647	125,022
42	81,152	124,071	124,071

TABLE V

SCHEDULE DATA

	Milestones Scheduled (Cumulative)				Milestones Accomplished (Cumulative)			
	Project				Project			
Month	A	B	C	D	A	B	C	D
1	4	4	2	8	4	4	2	8
2	8	7	5	14	8	7	5	14
3	12	21	10	16	10	20	10	16
4	16	24	10	21	11	21	10	20
5	21	35	14	24	17	28	14	23
6	28	43	19	30	24	33	18	26
7	36	56	29	31	33	42	28	26
8	40	62	37	34	39	51	36	33
9	49	80	40	38	46	58	39	36
10	55	88	42	40	55	69	40	39
11	60	94	48	45	59	74	47	42
12	62	102	51	48	60	80	51	45
13	70	108	52	52	70	82	51	50
14	75	113	60	58	73	90	57	58
15	82	98	73	63	80	94	68	63
16	84	103	83	70	83	99	78	68
17	90	107	90	77	89	102	86	73
18	91	107	100	81	91	105	100	81
19	94	115	108	82	93	112	105	81
20	103	120	116	91	102	117	113	87
21	112	125	123	91	107	117	114	90

TABLE V (Continued)

	Milestones Scheduled (Cumulative)				Milestones Accomplished (Cumulative)			
	Project				Project			
Month	A	B	C	D	A	B	C	D
22	112	131	123	94	112	121	120	90
23	116	133	129	97	113	129	125	93
24	117	134	133	99	114	133	128	96
25	121	142	133	99	118	136	129	99
26	123	146	137	101	120	143	135	99
27	128	150	140	103	123	146	139	101
28	130	155	145	105	130	150	142	101
29	134	161	151	106	132	156	145	103
30	137	165	151	110	137	156	150	103
31	140	168	156	110	140	167	156	107
32	151	175	170	113	143	168	168	107
33	151	180	171	113	149	172	170	110
34	154	183	179	116	150	182	176	114
35	158	190	184	120	156	190	181	115
36	159	193	190	123	158	193	190	122
37	159	199	189	128	159	196	189	127
38	162	201	191	132	162	200	190	131
39	166	202	194	133	165	202	193	133
40	167	212	198	137	166	206	197	137
41	169	213	198	138	169	213	198	137
42	174	213	198	138	169	213	198	137

Analysis and Results

The approach to data analysis for the first proposed method of solution is very simple and straightforward. A model, developed to some degree by experience and intuition rather than by a more scientific method, has been suggested. The model to be used is from equation (2.8):

$$\text{Predicted Cost} = \frac{\text{Contractor's Estimate}}{\text{Value Index}}$$

The data analysis phase for this approach will consist of calculating the Schedule Index from the data collected and recorded in Table V, calculating the Cost Index from the data collected and recorded in Tables I through IV, and then obtaining the Value Index by multiplying the calculated values of the Schedule Index by the Cost Index. Once the Value Index has been calculated in this manner for each of the 42 months, it will be divided into the respective Contractor's Estimate to provide a total program "Predicted Cost." This procedure will be used on each of the four sets of project data.

A computer program, the "Predicted Cost Program," was developed to perform the described calculations. A description of this computer program is given in Appendix A. The resulting output from this program is shown in Tables VI through IX.

By comparing the "Predicted Cost" column with the "Actual Cost" for each of these projects (Tables VI through IX), one notices that the model does not accurately predict the total actual cost. The following considerations

TABLE VI

PROJECT "A" PREDICTED COST PROGRAM VALUES

MONTH	SCHEDULE INDEX	COST INDEX	VALUE INDEX	PREDICTED COST	ACTUAL COST
1	1.000	0.849	0.849	446,126	506,759
2	1.000	0.865	0.865	440,525	
3	0.833	0.884	0.736	502,774	
4	0.688	0.884	0.608	612,179	
5	0.810	0.877	0.710	528,272	
6	0.857	0.867	0.743	604,757	
7	0.917	0.887	0.813	557,622	
8	0.975	0.883	0.861	538,759	
9	0.939	0.851	0.799	579,412	
10	1.000	0.827	0.827	575,502	
11	0.983	0.808	0.794	692,091	
12	0.968	0.848	0.821	707,308	
13	1.000	0.885	0.885	659,365	
14	0.973	0.930	0.905	659,336	
15	0.976	0.925	0.903	658,743	
16	0.988	0.904	0.893	658,453	
17	0.989	0.873	0.863	686,696	
18	1.000	0.841	0.841	698,303	
19	0.989	0.842	0.833	697,950	
20	0.990	0.837	0.829	667,468	
21	0.955	0.826	0.789	684,152	
22	1.000	0.822	0.822	667,246	
23	0.974	0.824	0.803	729,574	
24	0.974	0.822	0.801	726,795	
25	0.975	0.826	0.805	719,574	
26	0.976	0.824	0.804	712,255	
27	0.961	0.823	0.791	717,433	
28	1.000	0.835	0.835	692,182	
29	0.985	0.845	0.832	678,244	
30	1.000	0.851	0.851	669,268	
31	1.000	0.853	0.853	663,453	
32	0.947	0.849	0.804	670,638	
33	0.987	0.848	0.837	665,572	
34	0.974	0.855	0.833	660,690	
35	0.987	0.868	0.857	647,318	
36	0.935	0.869	0.813	654,950	
37	1.000	0.873	0.873	640,780	
38	1.000	0.877	0.877	635,139	
39	0.994	0.876	0.871	631,292	
40	0.994	0.872	0.867	627,336	
41	1.000	0.871	0.871	623,697	
42	0.971	0.867	0.842	618,557	

TABLE VII

PROJECT "B" PREDICTED COST PROGRAM VALUES

MONTH	SCHEDULE INDEX	COST INDEX	VALUE INDEX	PREDICTED COST	ACTUAL COST
1	1.000	1.091	1.091	335,400	801,832
2	1.000	0.961	0.961	383,878	
3	0.952	0.922	0.878	448,632	
4	0.875	0.924	0.809	487,327	
5	0.800	0.953	0.762	514,131	
6	0.767	0.927	0.711	597,292	
7	0.750	0.933	0.700	601,428	
8	0.823	0.921	0.758	568,262	
9	0.725	0.893	0.647	646,771	
10	0.784	0.883	0.692	617,304	
11	0.787	0.874	0.688	622,915	
12	0.784	0.852	0.668	645,362	
13	0.759	0.832	0.631	686,706	
14	0.796	0.821	0.654	677,488	
15	0.959	0.798	0.765	968,717	
16	0.961	0.787	0.756	979,097	
17	0.953	0.775	0.739	1,037,059	
18	0.981	0.761	0.747	1,025,940	
19	0.974	0.745	0.726	1,037,939	
20	0.975	0.720	0.702	1,054,376	
21	0.936	0.696	0.651	1,106,577	
22	0.924	0.687	0.635	1,114,336	
23	0.970	0.670	0.650	1,108,430	
24	0.993	0.660	0.655	1,108,133	
25	0.958	0.657	0.629	1,127,596	
26	0.979	0.646	0.632	1,129,259	
27	0.973	0.634	0.617	1,142,718	
28	0.968	0.630	0.610	1,149,582	
29	0.969	0.621	0.602	1,181,671	
30	0.945	0.616	0.582	1,201,395	
31	0.994	0.608	0.604	1,186,032	
32	0.960	0.593	0.569	1,293,658	
33	0.956	0.582	0.556	1,302,642	
34	0.995	0.575	0.572	1,288,274	
35	1.000	0.565	0.565	1,289,519	
36	1.000	0.558	0.558	1,270,727	
37	0.985	0.550	0.542	1,279,469	
38	0.995	0.544	0.541	1,278,939	
39	1.000	0.538	0.538	1,280,896	
40	0.972	0.533	0.518	1,292,908	
41	1.000	0.527	0.527	1,282,586	
42	1.000	0.520	0.520	1,289,108	

TABLE VIII

PROJECT "C" PREDICTED COST PROGRAM VALUES

MONTH	SCHEDULE INDEX	COST INDEX	VALUE INDEX	PREDICTED COST	ACTUAL COST
1	1.000	0.858	0.858	255,006	463,979
2	1.000	0.926	0.926	236,210	
3	1.000	0.950	0.950	330,752	
4	1.000	0.951	0.951	328,462	
5	1.000	0.884	0.884	356,401	
6	0.947	0.891	0.844	388,873	
7	0.966	0.897	0.867	377,837	
8	0.973	0.864	0.841	388,411	
9	0.975	0.864	0.842	454,726	
10	0.952	0.834	0.794	488,419	
11	0.979	0.827	0.810	478,617	
12	1.000	0.824	0.824	469,480	
13	0.981	0.787	0.772	497,544	
14	0.950	0.777	0.738	459,289	
15	0.932	0.766	0.714	473,545	
16	0.940	0.752	0.707	479,536	
17	0.956	0.728	0.696	459,253	
18	1.000	0.705	0.705	460,704	
19	0.972	0.691	0.672	466,462	
20	0.974	0.679	0.661	521,231	
21	0.927	0.671	0.622	532,497	
22	0.976	0.653	0.637	530,220	
23	0.969	0.646	0.626	553,150	
24	0.962	0.640	0.616	556,446	
25	0.970	0.630	0.611	562,334	
26	0.985	0.624	0.615	555,723	
27	0.993	0.619	0.615	557,665	
28	0.979	0.611	0.598	571,314	
29	0.960	0.608	0.584	584,525	
30	0.993	0.606	0.602	581,776	
31	1.000	0.595	0.595	591,995	
32	0.988	0.587	0.580	601,045	
33	0.994	0.577	0.574	656,717	
34	0.983	0.565	0.555	663,651	
35	0.984	0.559	0.550	664,509	
36	1.000	0.553	0.553	707,093	
37	1.000	0.546	0.546	710,492	
38	0.995	0.537	0.534	720,407	
39	0.995	0.528	0.525	720,135	
40	0.995	0.524	0.521	719,646	
41	1.000	0.520	0.520	719,832	
42	1.000	0.513	0.513	722,504	

TABLE IX

PROJECT "D" PREDICTED COST PROGRAM VALUES

MONTH	SCHEDULE INDEX	COST INDEX	VALUE INDEX	PREDICTED COST	ACTUAL COST
1	1.000	1.956	1.956	30,702	124,071
2	1.000	2.029	2.029	29,143	
3	1.000	2.098	2.098	27,633	
4	0.952	1.899	1.808	31,746	
5	0.958	1.734	1.661	34,315	
6	0.867	1.583	1.372	59,941	
7	0.839	1.622	1.361	60,023	
8	0.971	1.631	1.584	51,867	
9	0.947	1.601	1.516	61,938	
10	0.975	1.577	1.538	60,898	
11	0.933	1.462	1.364	68,682	
12	0.938	1.343	1.260	84,264	
13	0.962	1.424	1.370	76,190	
14	1.000	1.405	1.405	75,013	
15	1.000	1.275	1.275	83,025	
16	0.971	1.194	1.159	90,843	
17	0.948	1.107	1.049	110,100	
18	1.000	1.039	1.039	110,838	
19	0.988	0.990	0.978	115,798	
20	0.956	0.970	0.927	123,864	
21	0.989	0.932	0.922	124,444	
22	0.957	0.904	0.865	131,221	
23	0.959	0.873	0.837	135,931	
24	0.970	0.805	0.781	144,514	
25	1.000	0.816	0.816	138,706	
26	0.980	0.804	0.788	142,819	
27	0.981	0.779	0.764	147,260	
28	0.962	0.775	0.746	150,741	
29	0.972	0.769	0.747	150,670	
30	0.936	0.759	0.710	157,198	
31	0.973	0.754	0.734	155,187	
32	0.947	0.740	0.701	164,556	
33	0.973	0.730	0.710	163,250	
34	0.983	0.722	0.710	163,205	
35	0.958	0.717	0.687	163,729	
36	0.992	0.697	0.691	164,503	
37	0.992	0.679	0.674	168,347	
38	0.992	0.676	0.671	167,665	
39	1.000	0.668	0.668	163,126	
40	1.000	0.663	0.663	163,889	
41	0.993	0.658	0.653	165,096	
42	0.993	0.654	0.649	163,920	

indicate that this approach does not present a satisfactory solution to the problem.

1. There is no pattern to the cost predictions from project to project, especially in the early months, which are of vital concern in this study. Project "A" estimates substantially higher than actual in the early months; Project "B" estimates substantially lower than actual; Project "C" estimates closest of the four, but somewhat low; and Project "D" estimates substantially lower than actual in the early months.
2. In the last half of the 42-month time span, all four programs predict total costs far in excess of the actual costs.
3. The variance of predicted versus actual cost ranges from -75 percent to +68 percent.
4. The predicted cost is largely dependent on the contractor's estimate and varies relative to it. There is, therefore, no leveling off or constant cost prediction, but rather a continuing increase in the predicted estimate.

Thus it is concluded that this approach does not satisfy the thesis of this investigation. Although a simplified method for calculation and maintenance of a Value Index of contractor performance has been presented, it appears that this Value Index alone is not an appropriate adjustment factor to the contractor's estimate to provide a valid prediction of total cost for the project. This conclusion encourages the search for additional factors that might be used to adjust the contractor's estimate and perhaps a more systematic approach to development of a model.

CHAPTER III

PROBLEM SOLUTION — METHOD II

The Approach

A more deliberate and scientific method is designed for the second approach to development of a cost prediction model that will satisfy the objectives of this investigation. It has been concluded from the first approach that the Value Index alone does not provide the proper adjustment factor to the contractor's estimate in order to provide a reliable forecasting technique. Yet, the study objective remains — the definition of an adjustment factor which when applied to the contractor's estimate of project cost will provide a forecast that varies less from the actual cost than did the contractor's estimate. The area of concentration is thus defined as the variation of the contractor's estimate of the total project cost from the total cost that is finally incurred on the contract. The best estimate the project manager has available is the contractor's estimate, which has very poor forecasting capability, especially in the early months of the contract. Therefore, if factors that cause this estimate to vary from actual cost can be identified and some mathematical function developed to relate these factors to the amount of variability, then this relationship should, in effect, serve as a predictive model.

The variation being discussed needs precise definition. In order to provide some consistency in comparison of the amount of variation from project to project, a percentage deviation figure seems logical. The variation of the contractor's estimate from actual cost can most easily be described as a percentage of the actual cost. Therefore, the variation, designated Y, can be described as the following ratio:

$$Y = \frac{\text{Actual Cost} - \text{Contractor's Estimate}}{\text{Actual Cost}}$$

or

$$Y = \frac{AC - CE}{AC} \tag{3.1}$$

The resulting ratio multiplied by 100 gives the percentage variation.

It is obvious that if an appropriate mathematical relationship can be established between this ratio and the variables that affect it, then this relationship can be used to predict the ratio if certain values for the variables are known. Once the ratio has been predicted, it is an easy task to substitute the most recent contractor's estimate into equation (3.1) and solve for the resulting forecast of the actual cost. This is more clearly seen if equation (3.1) is rearranged as follows:

$$AC = \frac{CE}{1 - Y} \tag{3.2}$$

Shown in this form, the forecast of actual cost is obviously dependent on the contractor's estimate adjusted by related factors which are taken into account in the ratio, Y.

The ratio, Y, is clearly a variable quantity over the life cycle of the contract. There are, without doubt, variable factors that affect this ratio and are therefore related to the response or change that occurs. This type situation suggests the use of regression analysis as the systematic technique which can be used to obtain a mathematical relationship between these variables. Investigation will show that at least four independent variables should be considered; therefore, multiple regression methods will be required.

The objective of the regression analysis will be to "explain" as much of the variation in the ratio, Y, as possible in terms of the four independent variables. This is done by (1) forming a theory concerning what factors affect the ratio, (2) collecting necessary data, and (3) performing multiple regression analysis by computer techniques on various combinations of the model factors. Thus, an attempt is made to find the combination of explanatory factors which accounts for the largest amount of the ratio variation.

There are potentially several independent variables that might affect the variance between the contractor's estimate and the actual cost. While it would seem logical that the more variables included in the regression equation, the more accurately it would predict, this is not always the case. In the first place, a large portion of the change in the dependent variable may be explained by one or only a few independent variables, and additional variables may not significantly increase the precision of the prediction.

Secondly, the objective may be to develop a simplified model, as is the case with this study, that avoids addition of a large number of variables which increases the difficulty of obtaining data and applying the model. After careful consideration of the potential variables, the data available, and preliminary plots of the data, three independent variables in addition to the Value Index were chosen for the regression analysis.

It is assumed in choosing these four independent variables and limiting the analysis to these four, that a significant regression can be defined which will result in an adequate predictive model. Once the regression equation has been developed, this assumption will be verified by appropriate significance tests. The model itself will be tested, and its resulting predictions compared to those of the best available prediction — the contractor's estimate. Only then can it be determined if additional independent variables must be considered.

Additional Data

Values for the dependent variable, Y, as defined in equation (3.1), for each of the four projects considered in this investigation, are presented in Tables X through XIII. These values result from a computer program written to perform these calculations. The program, referred to as the "Ratio Program," is described in Appendix B. (The program also calculated the Contract Value (C.V.) variable to be discussed below.)

TABLE X

PROJECT "A" — VALUES OF Y AND C.V. RATIOS

MONTH	RATIO	C.V. CHANGE
1	.2526	.000
2	.2481	.009
3	.2698	.009
4	.2655	.041
5	.2599	.042
6	.1133	.039
7	.1266	.039
8	.1204	.076
9	.1034	.076
10	.0863	.081
11	-.0689	.342
12	-.1223	.346
13	-.1084	.343
14	-.1284	.330
15	-.1253	.330
16	-.1148	.330
17	-.1330	.330
18	-.1292	.338
19	-.1231	.338
20	-.0705	.340
21	-.0715	.341
22	-.0658	.339
23	-.1527	.340
24	-.1468	.341
25	-.1383	.340
26	-.1260	.342
27	-.1248	.342
28	-.1150	.341
29	-.0901	.341
30	-.0872	.341
31	-.0781	.341
32	-.0738	.341
33	-.0765	.341
34	-.0672	.343
35	-.0521	.344
36	-.0517	.344
37	-.0455	.345
38	-.0368	.345
39	-.0286	.345
40	-.0208	.346
41	-.0156	.347
42	.0000	.346

TABLE XI

PROJECT "B" — VALUES OF Y AND C.V. RATIOS

MONTH	RATIO	C.V. CHANGE
1	.5435	.004
2	.5398	.151
3	.5086	.157
4	.5081	.158
5	.5112	.158
6	.4702	.160
7	.4726	.186
8	.4718	.187
9	.4654	.196
10	.4634	.203
11	.4608	.215
12	.4538	.291
13	.4438	.291
14	.4361	.291
15	.0860	.291
16	.0854	.352
17	.0494	.352
18	.0509	.352
19	.0540	.357
20	.0559	.365
21	.0492	.360
22	.0553	.360
23	.0485	.458
24	.0449	.458
25	.0495	.461
26	.0458	.467
27	.0474	.470
28	.0478	.471
29	.0303	.520
30	.0331	.520
31	.0364	.525
32	-.0275	.559
33	-.0273	.561
34	-.0251	.947
35	-.0226	.948
36	-.0061	2.264
37	-.0046	2.264
38	-.0037	2.265
39	-.0036	2.380
40	-.0018	2.384
41	.0005	2.384
42	-.0003	2.384

TABLE XII

PROJECT "C" — VALUES OF Y AND C.V. RATIOS

MONTH	RATIO	C.V. CHANGE
1	.5284	.000
2	.5286	.000
3	.3228	.033
4	.3268	.052
5	.3210	.166
6	.2926	.166
7	.2985	.173
8	.2954	.353
9	.1744	.358
10	.1544	.358
11	.1578	.358
12	.1623	.475
13	.1581	.475
14	.2487	.476
15	.2458	.555
16	.2425	.555
17	.2821	.647
18	.2728	1.035
19	.2748	1.035
20	.2003	1.047
21	.2025	1.069
22	.1986	1.071
23	.1728	1.071
24	.1735	1.072
25	.1684	1.072
26	.1750	1.072
27	.1724	1.118
28	.1637	1.199
29	.1548	1.218
30	.1479	1.218
31	.1358	1.266
32	.1270	1.266
33	.0592	1.349
34	.0567	1.721
35	.0573	1.721
36	.0056	1.725
37	.0045	1.390
38	-.0019	1.745
39	.0024	1.751
40	.0047	1.751
41	.0050	1.753
42	.0051	1.758

TABLE XIII

PROJECT "D" — VALUES OF Y AND C.V. RATIOS

MONTH	RATIO	C.V. CHANGE
1	.5160	.001
2	.5234	.003
3	.5327	.005
4	.5374	.006
5	.5406	.006
6	.3372	.006
7	.3412	.006
8	.3457	.017
9	.2486	.017
10	.2513	.017
11	.2446	.041
12	.1401	.142
13	.1586	.142
14	.1518	.142
15	.1432	.142
16	.1434	.175
17	.0570	.250
18	.0594	.250
19	.0594	.250
20	.0338	.319
21	.0332	.343
22	.0288	.403
23	.0195	.328
24	.0127	.331
25	.0190	.340
26	.0171	.358
27	.0113	.363
28	.0072	.336
29	.0067	.336
30	.0049	.333
31	.0049	.329
32	-.0322	.335
33	-.0297	.351
34	-.0295	.351
35	-.0198	.381
36	-.0263	.378
37	-.0378	.201
38	-.0324	.201
39	-.0062	.230
40	-.0075	.230
41	-.0084	.252
42	.0000	.257

The three independent variables, in addition to the Value Index, to be considered in the regression analysis can be defined as follows:

1. Percent Change in Contract Value (C. V.) — defined by the following ratio:

$$\frac{\text{Present Contract Value} - \text{Baseline Contract Value}}{\text{Baseline Contract Value}} \qquad (3.3)$$

where the Contract Value refers to the negotiated price of the contract plus all changes to the contract approved by the project manager, but which may or may not be presently funded in the contract. The approved updated contract value appears in the monthly Contractor Financial Report (NASA Form 533).

2. Wage Index (W. I.) — the "Average Hourly Earnings in the Aerospace Industry," calculated monthly and reported by the Aerospace Industries Association of America, Inc., Washington, D.C.

3. Time Remaining on the Contract — defined as the following ratio:

$$\frac{\text{Months Remaining on Contract}}{\text{Duration of Contract in Months}} \qquad (3.4)$$

The Contract Value variable attempts to measure the change in the value of the contract from its initiation to the present. It is easily seen that this variable could affect the variance between the contractor's estimate and the actual cost. As changes are approved and added each month to the contract, the contractor reflects this change by an appropriate adjustment (predominantly an increase) in his prediction of the total contract cost. The factor that is not taken into account by the contractor's estimate, however, is the continuing trend of contract value change from the present time when he makes his estimate until the end of the contract. This factor is considered by the regression analysis. Tables X through XIII show the "Percent Change in Contract Value" figures for the four projects considered in this study as calculated by the "Ratio Program."

The Wage Index is an indication of the increase in aerospace labor costs over the life cycle of the contract. Although the contractor may attempt to make allowance for a cost of living increase in his prediction, the Wage Index accounts for the actual increase in costs as updated monthly by the Aerospace Industries Association. The Wage Index is considered an entirely sufficient index of the trend for the total contract cost (labor, material, and burden) since the largest portion by far of the total cost of R&D contracts is labor. Studies within NASA on the same contracts used for data support in this investigation showed total labor cost to represent 80 to 90 percent of the total cost of the contract. The Wage Index values for the four programs over the time period considered here are presented in Table XIV.

The Time Remaining ratio described in equation (3.4) becomes smaller as the contractor's estimate draws closer to actual cost. This suggests that the time at which the contractor is making his prediction in relation to the duration over which he is predicting may influence the variance ratio, Y. Calculated values of the Time Remaining variables are shown in Table XV.

TABLE XIV

WAGE INDEX VALUES

Month	Avg. Hr. Earnings ($)	Month	Avg. Hr. Earnings ($)
1	3.13	22	3.46
2	3.13	23	3.46
3	3.14	24	3.47
4	3.13	25	3.48
5	3.15	26	3.49
6	3.14	27	3.49
7	3.16	28	3.47
8	3.17	29	3.47
9	3.18	30	3.48
10	3.26	31	3.50
11	3.26	32	3.54
12	3.26	33	3.57
13	3.36	34	3.59
14	3.36	35	3.60
15	3.34	36	3.64
16	3.34	37	3.64
17	3.39	38	3.63
18	3.37	39	3.62
19	3.38	40	3.59
20	3.41	41	3.63
21	3.44	42	3.64

TABLE XV

TIME REMAINING RATIO VALUES

Month	T. R.	Month	T. R.
1	1.000	22	0.500
2	0.976	23	0.476
3	0.952	24	0.452
4	0.928	25	0.428
5	0.905	26	0.405
6	0.881	27	0.381
7	0.857	28	0.357
8	0.833	29	0.333
9	0.809	30	0.309
10	0.786	31	0.286
11	0.762	32	0.262
12	0.738	33	0.238
13	0.714	34	0.214
14	0.690	35	0.190
15	0.667	36	0.167
16	0.643	37	0.143
17	0.619	38	0.119
18	0.595	39	0.095
19	0.571	40	0.072
20	0.548	41	0.048
21	0.524	42	0.024

Simple correlation coefficients for each of the four independent variables when considered alone with the dependent variable, Y, were calculated and the results are as follows:

Percent Change in Contract Value versus Y: -0.3095

Value Index versus Y: 0.4523

Wage Index versus Y: -0.7480

Time Remaining versus Y: 0.7098

A comparison of these coefficients with tabular values from Yamane (20) indicates that each of these four variables is significantly correlated to the dependent variable, Y, at the one percent level. All the assumptions for Approach I as stated in Chapter II hold for this approach and need not be restated.

Sample Population Similarity

In the first approach to developing a solution to the study problem, the proposed model was tested separately on each of the four projects being considered. This was possible since the model development was not dependent on an empirical data base and there were sufficient sample data points in each of the projects to test the model.

In the regression approach to development of a model, it will be wise to combine data from at least three of the projects to use as the input observations to the regression program. Data from projects "A," "B," and "D" will be combined thus permitting 126 data points or observations for the regression analysis, a very adequate sample size. This will leave Project "C," or 42 data points, as a test case for the developed model.

To combine the data, however, it must first be determined if the data from the individual projects can be considered as samples derived from the same population. This is necessary in order to decide if the differences in the data from project to project indicate differences among the populations or whether the differences occur as random variables from the same population.

There are several tests available for determining if it is likely that two or more samples came from the same universe. However, nonparametric tests, whose models do not specify conditions about the parameters of the sample populations, can be used with fewer and weaker assumptions than those associated with parametric tests (21).

Additional assumptions can be avoided by using ranks rather than the original observations; that is, the N observations are arrayed in order of magnitude and the smallest is replaced by one, the next-to-smallest by two, and so on, the largest being replaced by N. By using ranks, the only assumptions underlying the use of the Kruskal-Wallis (22) H-Test employed here are that the observations are independent, that all those within a given sample come from a single population, and that the populations are of approximately the same form.

The H-Test is based on the following test statistic:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{c} \frac{R_i^2}{n_i} - 3(N+1) \qquad (3.5)$$

where,

c = number of samples.

n_i = the number of observations in the i^{th} sample.

$N = \sum n_i$, the number of observations in all samples combined.

R_i = the sum of the ranks in the i^{th} sample.

H is distributed as $\chi^2_{(c-1)}$ and large values of H lead to rejection of the hypothesis that all samples come from the same population. Values for the dependent variable, Y, from each of the four projects were summed within 6-month periods for testing purposes. This provided four samples of seven observations each for each of the four projects. These values are shown in Table XVI.

The values are ranked for $N = 28$ values as shown also in Table XVI, and below these values are shown the calculations necessary for substitution into the test statistic, equation (3.5). Substitution of the calculated values into this equation gives the following results:

$$H_{cal} = \frac{12(6452.28)}{28(29)} - 3(29) = 8.35$$

The chi-square table value for $c - 1 = 6$ degrees of freedom at the $0.05\ \alpha$ level is 12.59. Since the 8.35 calculated value is less than the 12.59 table value, we cannot reject the hypothesis that all samples came from the same population. Therefore, it can be concluded, on a statistical basis that the four projects were derived from the same population. This conclusion permits the use of the combined observations from three of the projects for

TABLE XVI

POPULATION SIMILARITY TEST

	PROJECT			
	A	B	C	D
		Sample Values		
	1.4092	3.0814	2.3202	2.9873
	0.2455	2.7878	1.2428	1.5715
	-0.7391	1.1516	1.4500	0.7134
	-0.6304	0.3078	1.2225	0.1874
	-0.6814	0.2539	0.9822	0.0662
	-0.3994	-0.0722	0.4416	-0.1326
	-0.1473	-0.0145	0.0198	-0.0923
		Ranking		
	1	8	10	6
	2	9	16	7
	3	14	18	11
	4	15	20	12
	5	19	21	17
	13	26	25	24
	22	28	23	27
R	50	119	133	104
$\frac{R^2}{n}$	357.14	2023.0	2527.0	1545.14

$$\sum \frac{R^2}{n} = 6452.28$$

the regression analysis phase of the study; data from the fourth project will be used to validate the model.

The Multiple Regression Model

It is possible at this point to precisely define the regression problem in terms of the variables previously defined. The dependent variable is Y, a ratio as defined by equation (3.1). The regression equation will be found that describes the relationship between this dependent variable, Y, and four independent variables as follows:

X_1 — Percent Change in Contract Value (C.V.) as defined in equation (3.3)

X_2 — Value Index (V.I.) as defined in equation (2.3).

X_3 — Wage Index (W.I.) as shown in Table XIV.

X_4 — Time Remaining (T.R.) as shown in Table XV.

Two regression equations will be developed. In the first phase of the regression analysis, termed Regression I, it will be assumed that a linear relationship exists between these variables of the form

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \mu \qquad (3.6)$$

The unknown parameters, $\beta_0, \ldots, \beta_4$, are called the regression coefficients, and μ is a random variable, the unexplained error remaining after the regression line has been fitted that indicates the increment by which any individual Y value falls off the regression line (or surface).

In the second phase of the analysis, termed Regression II, a regression equation will be developed including the squares and cross-products of the original four input variables as independent variables. The procedure used for estimating the coefficients in both regressions will be the method of least squares. This method minimizes the sum of squares of the error term or residuals.

The computer program selected for the regression analysis is called the "Nonsimple Stepwise Regression Program." A tabular listing of the values this program produced for Regression I and Regression II are given in Appendix C.

The regression procedure used in the "Nonsimple Stepwise Regression Program" is designed to ultimately select the "best" regression equation in terms of goodness of fit. The value used to evaluate the goodness of fit is R^2 as achieved by the least squares fit. R^2 is called the "coefficient of multiple determination" and shows the relative reduction in the total sum of squares when a regression surface is fitted (20). For example, when $R^2 = 0.7$, it means that there has been a 70 percent reduction in the total sum of squares. Hence, R^2 shows the amount of improvement (in terms of reducing the total error) brought about by fitting the regression surface to the actual points relative to the fit of the plane going through the mean $(\overline{Y}, \overline{X}_1 \ldots \overline{X}_k)$, where k is the number of independent variables in the regression equation.

The program selects the set of variables from all possible subsets of the constant term, β_0, plus the variables $X_1 \ldots . X_k$ that results in the highest R^2 value.

The first step of the program is a regression on one independent variable selected as the variable possessing the highest simple correlation with the dependent variable. Variables are then added one at a time to the regression set. Also at each step, a deletion step is always tried to determine if a better set of one fewer elements can be found. Thus, if at any step, a subset, S, of variables has been found, and if by deleting a variable from S, a subset S' is found for which the R^2 value is increased, then S is replaced by S'. Next, the possible deletion of a second variable is considered, and so on. If, however, a deletion step does not yield a better set, then an adjunction step follows and the cycle is repeated. This process is continued until all variables are considered, and, thus the "best" set of variables is included in the ultimate regression equation.

Draper and Smith (23) point out that in using R^2 as a measure of the success of the regression equation, the improvement in R^2 caused by adding another variable should have some real significance and not result from the fact that the number of parameters in the model is approaching the number of observations. A check should be made to determine the change in the residual mean square and in the R^2 value. It is possible that as a variable is added which increases R^2, it at the same time increases the residual mean square value, since one degree of freedom is removed from the residual degrees of freedom.

Since the second regression included the larger number of potential parameters in the model, a check was made at 5-step intervals in the 21-step analysis to verify that the residual mean square error term was in fact reducing while the R^2 value increased. Results shown in Table XVII indicate that the residual mean square error was reduced consistently as the coefficient of multiple determination, R^2, was increased.

The first phase of the regression analysis considered only the four independent variables X_1, X_2, X_3, X_4. Results of this regression are shown in Tables XVIII and XIX.

TABLE XVII

RESIDUAL MEAN SQUARE VALUE VERSUS R^2

Regression Step	R^2	d.f.	Residual S.S.	Residual M.S.
1	0.62127	124	1.88195	0.01518
6	0.71380	121	1.42167	0.01175
11	0.73100	118	1.33623	0.01132
16	0.76016	119	1.19160	0.01001
21	0.77859	115	1.10025	0.00957

TABLE XVIII

REGRESSION I EQUATION

Variable	Coefficient	Std. Error
Constant	5.2230	
X_1	0.0506	0.028145
X_2	0.0870	0.04534
X_3	-1.4804	0.33725
X_4	-0.3595	0.19941

TABLE XIX

REGRESSION I AOV

Source	d.f.	S.S.	M.S.	F
Regression	4	2.9388	0.7347	43.78
Residual	121	2.0303	0.01678	
Total	125	4.9691		

The R^2 value for Regression I was 0.591 indicating that about 59 percent of the total error has been reduced by fitting the regression plane. The $F_{.01(4, 121)}$ table value is 3.48; therefore, a highly significant overall regression is indicated.

As discussed earlier, the "Nonsimple Stepwise Regression Program" has the capability of considering all squares and cross-products of designated input variables and the input variables, as the regression independent variables. On this basis, fourteen potential independent variables were created as follows:

X_1	$X_8 = X_1X_4$
X_2	$X_9 = X_2X_2$
X_3	$X_{10} = X_2X_3$
X_4	$X_{11} = X_2X_4$
$X_5 = X_1X_1$	$X_{12} = X_3X_3$
$X_6 = X_1X_2$	$X_{13} = X_3X_4$
$X_7 = X_1X_3$	$X_{14} = X_4X_4$

The results of the second regression analysis are shown in Tables XX and XXI.

The R^2 value for Regression II was 0.778 indicating that about 78 percent of the total error has been reduced by fitting the regression plane while including squares and cross-products as potential variables. The $F_{.01(10,115)}$ table value is 2.19 indicating a highly significant overall regression.

In the regression analysis, certain assumptions have been made about the error term, μ, of equation (3.6). The usual assumptions are that the

TABLE XX

REGRESSION II EQUATION

Variable	Coefficient	Std. Error
Constant	-0.63162	
X_1	5.13668	2.1772
X_3	-0.04732	0.3421
X_5	-0.06155	0.0772
X_6	-4.02251	0.6962
X_7	-0.80528	0.5746
X_8	1.25675	0.37522
X_9	0.24118	0.11602
X_{10}	0.36351	0.11382
X_{11}	-1.71897	0.30567
X_{14}	1.50672	0.22086

TABLE XXI

REGRESSION II AOV

Source	d.f.	S.S.	M.S.	F
Regression	10	3.8689	0.38689	40.04
Residual	115	1.1002	0.00957	
Total	125	4.9691		

errors are independent, have zero mean, a constant variance, and follow a normal distribution, which is required for making the F-test (23). In the next chapter, the assumption of normality will be tested with the residual terms of Regression II in order to associate probabilities with resulting predictions from the model. This test, which verifies that the normality assumption is a reasonable one, also strengthens the significance of the overall regression as tested by the F-test.

An empirical model has now been obtained that can be used for predictive purposes. Created on the assumption that four independent variables could be used to explain the variation in a dependent variable, it provides no explanation for variation in the independent variables, but merely supplies an adequate empirical explanation of the data that may be useful in future work (23).

Since both regressions are shown to be highly significant and since Regression II results in a larger coefficient of multiple determination (and correspondingly a smaller residual mean square value), Regression II will be accepted as the model to be tested. It should also be noted that even though six independent variables have been added to the model by this choice, this fact does not significantly increase the difficulty of implementing the model. The additional variables result from squares and cross-products of the four basic independent variables, and therefore, do not require that any additional data be available.

CHAPTER IV

MODEL VALIDATION AND APPLICATION

Interpretation of Predictive Results

The predictive value of the model will be evaluated using the Regression II equation as a model and the 42 observations of Project "C" as a test case. A computer program, the "Test Program," was written to perform the model calculations. This program is described in Appendix D. Output from the program is shown in Table XXII. This table shows the calculated ratio, or Y, and the actual ratio for each of the 42 months of the test program. The deviation between the two values is also shown.

By the use of equation (3.2) and given the contractor's estimate for each of the months considered, the "Test Program" also calculated the predicted actual costs. These predictions are listed in Table XXIII. The contractor's estimate, which represents the best estimate previously available to the project manager, is also shown. Percent deviations of the regression estimate (RE) and the contractor's estimate (CE) from the actual cost are listed for comparison. Four points have been eliminated from the predicted results: the two first months when the prediction cannot be expected to be reliable since the model has not had sufficient time to stabilize, and months

TABLE XXII

TEST PROGRAM RESULTS

MO	CALC. RATIO	ACTUAL RATIO	DEVIATION
1	.4059	.5284	-.1225
2	.3624	.5286	-.1662
3	.3321	.3228	.0093
4	.2986	.3286	-.0300
5	.3073	.3210	-.0137
6	.2977	.2926	.0051
7	.2550	.2985	-.0435
8	.2792	.2954	-.0162
9	.2432	.1744	.0688
10	.2666	.1544	.1122
11	.2138	.1578	.0560
12	.1749	.1623	.0126
13	.2087	.1581	.0506
14	.2271	.2487	-.0216
15	.2623	.2458	.0165
16	.2401	.2425	-.0024
17	.2426	.2821	-.0395
18	.2854	.2728	.0126
19	.3531	.2748	.0783
20	.3344	.2003	.1341
21	.4190	.2025	.2165
22	.3083	.1986	.1097
23	.3062	.1728	.1334
24	.2949	.1735	.1214
25	.2668	.1684	.0984
26	.2104	.1750	.0354
27	.1841	.1724	.0117
28	.2436	.1637	.0799
29	.2661	.1548	.1113
30	.1522	.1479	.0043
31	.1372	.1358	.0014
32	.1293	.1270	.0023
33	.1024	.0592	.0432
34	.1654	.0567	.1087
35	.1378	.0573	.0805
36	.0311	.0056	.0255
37	.0296	.0045	.0251
38	.0701	-.0019	.0720
39	.0949	.0024	.0925
40	.1197	.0047	.1150
41	.0388	.0050	.0338
42	.0305	.0051	.0254

TABLE XXIII

CONTRACTOR'S ESTIMATE VERSUS REGRESSION ESTIMATE
(Thousands of Dollars)

Actual Cost 463,979				
Month	Contractor Estimate	Percent Deviation	Regression Estimate	Percent Deviation
3	314,214	-32.3	470,451	1.4
4	312,367	-32.7	445,348	-4.0
5	315,058	-32.1	454,826	-2.0
6	312,066	-32.7	444,349	-4.2
7	325,496	-29.8	436,907	-5.8
8	326,956	-29.5	453,602	-2.2
9	383,061	-17.4	506,159	9.1
10	392,346	-15.4	534,969	15.3
11	390,768	-15.6	497,034	7.1
12	418,668	-9.8	507,415	9.4
13	390,643	-15.8	493,672	6.4
14	348,582	-24.9	451,005	-2.8
15	349,918	-24.6	474,336	2.2
16	351,474	-24.2	462,527	-0.3
17	332,082	-28.4	438,450	-5.5
18	377,420	-18.7	528,156	13.8
19	336,497	-27.5	520,168	12.1
22	371,825	-19.9	537,552	15.9

TABLE XXIII (Continued)

Actual Cost 463,979				
Month	Contractor Estimate	Percent Deviation	Regression Estimate	Percent Deviation
23	383,817	-17.3	553,210	19.2
24	383,470	-17.4	543,852	17.2
25	385,863	-16.8	526,273	13.4
26	382,785	-17.5	484,783	4.5
27	383,979	-17.2	470,620	1.4
28	388,024	-16.4	512,988	10.6
29	392,157	-15.5	534,347	15.1
30	395,345	-14.8	466,319	0.5
31	400,960	-13.6	464,720	0.2
32	405,058	-12.7	465,210	0.2
33	436,499	-5.9	486,296	4.6
34	437,660	-5.7	524,395	13.0
35	437,390	-5.7	507,295	9.3
36	461,387	-0.6	476,197	2.6
37	461,900	-0.4	475,989	2.6
38	464,852	0.2	499,895	7.7
39	462,863	-0.2	511,394	10.2
40	461,789	-0.5	524,581	13.1
41	461,681	-0.5	480,109	3.5
42	461,620	-0.5	476,142	2.6

20 and 21 during which time an undue increase in contract value occurred. The increase in contract value was significant enough to warrant a re-evaluation of the schedule and cost plans for the project which would necessitate establishing a new baseline for the predictive model. However, since in actuality, no such re-evaluation took place, the remaining data must be accepted. Since the area of primary concern is the early months (the first year or so), the value of the model is unaffected by removing points 20 and 21.

Snedecor and Cochran (24) suggest that when the purpose in developing a regression model is to provide a more accurate method of prediction than one presently available, the comparative size of the standard errors for the two predictors is important. Since this is the purpose in this investigation, the regression estimate will be compared with the contractor's estimate on this basis; that is, $\left[\left(Y - Y_{EST}\right)^2/\text{d.f.}\right]^{1/2}$, where Y_{EST} is either the regression or contractor estimate, and Y is the actual cost, both in dollars. The resulting calculations are shown in Table XXIV.

TABLE XXIV

IMPROVEMENT WITH REGRESSION ESTIMATE

Predictor	Std. Dev.	Avg. Percent Dev.
Contractor Estimate	9.156×10^4	16.07
Regression Estimate	4.982×10^4	7.13

Both the standard deviation and the average percent deviation indicate that the regression equation provides an improved prediction capability.

Figure 4 is a plot of the regression estimate and the contractor's estimate compared with the total actual cost of the program. This plot, showing data points through month 18 of the program, emphasizes the real value of the model in indicating trends of cost in the early months of the program. Circles represent the regression estimate while x's represent the contractor's estimate.

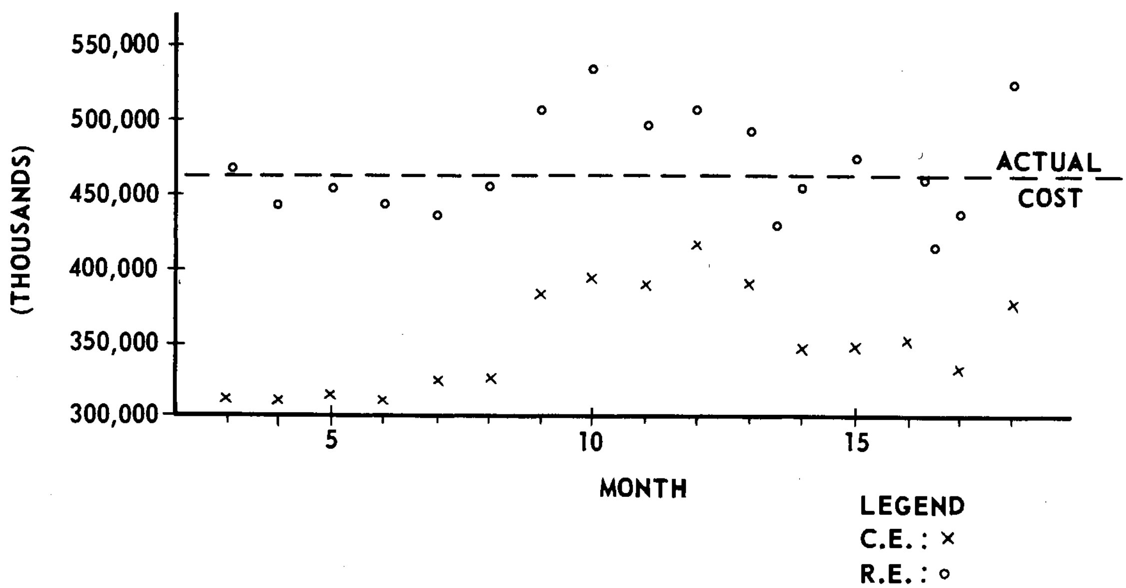

Figure 4. Early Prediction Capability

Approximately 18 months after the initiation of the project baseline, and 24 months (two full years) before the project completion date, the model prediction indicates a trend of cost much higher than the contractor is estimating. This, in itself, is more valuable information to the project manager at the time than precise dollar estimates. Such is true simply because this contract overrun trend warns the manager to re-evaluate the contract and perhaps even renegotiate with the contractor. If, in fact, a re-assessment is made of the contract in which the budget and schedule are replanned, then the model and the measurements supporting the variables can be reset to take the new plan into account. The management tool has served its purpose by providing the project manager with justification for re-assessment of the project plan and by encouraging the initiation of this action.

Costs and Assigned Probabilities

It is possible, by using the results of the regression, to determine the probability of the total program cost being over or under a given amount. This would be especially useful for indicating the probability, based on project data to date, of a cost overrun on the project.

In order to calculate probability values about the regression estimate, one must validate the assumption that the regression error terms or residuals are normally distributed. Statistical tests will be employed to determine whether the amount of agreement between the actual distribution of the residuals and a theoretical normal distribution is satisfactory. By establishing that the residuals could reasonably be normally distributed, one can interpret the standard error or mean square error values in terms of the normal distribution, where the regression estimate is used as the mean of the distribution and the standard error as the standard deviation (20).

Figure 5 shows the observed distribution of the residuals grouped in 0.05 intervals. Although the plot visually suggests that the data are probably normally distributed, two statistical tests will be used to verify this statement.

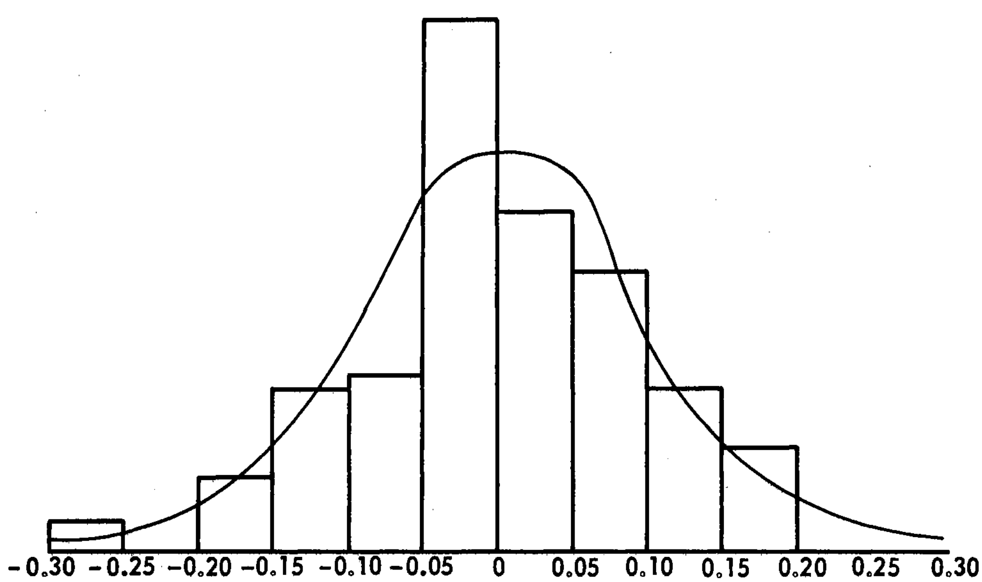

Figure 5. Distribution of Residuals

The Kolmogorov-Smirnov One-Sample test involves the cumulative frequency distributions of the observed and theoretical distributions. The maximum absolute difference between the two cumulative frequency distributions is determined and compared with a tabulated test statistic to establish whether a difference that large could have occurred by chance (21). Results of these calculations performed by a selected computer program are shown in Table XXV.

TABLE XXV

NORMALITY TEST

Interval	Observed		Normal	
	Frequency	Probability	Deviate	Probability
-0.30 to -0.25	2	0.01587	-2.7082	0.00338
-0.25 to -0.20	0	0.01587	-2.1665	0.01514
-0.20 to -0.15	5	0.05555	-1.6249	0.05209
-0.15 to -0.10	11	0.14286	-1.0833	0.13935
-0.10 to -0.05	12	0.23810	-0.0542	0.29404
-0.05 to 0	36	0.52381	0.0000	0.50000
0 to 0.05	23	0.70635	0.5416	0.70596
0.05 to 0.10	19	0.85714	1.0833	0.86065
0.10 to 0.15	11	0.94444	1.6249	0.94791
0.15 to 0.20	7	1.00000	2.1665	0.98486
0.20 to 0.25	0	1.00000	2.7082	0.99617
0.25 to 0.30	0	1.00000	3.2498	0.99942

The maximum absolute difference calculated for these distributions was 0.0559. At the 5 percent rejection level, the test statistic is $1.36/\sqrt{n} = 1.36/\sqrt{126} = 0.12$. Since the calculated value is less than the tabulated value, the hypothesis of normality cannot be rejected.

The particular computer program used also calculates the χ^2 value for the "chi-square goodness of fit" test. This test also substantiated the normality assumption. The χ^2 calculated value is 7.1868 compared with a tabular ${}_{.05}\chi^2_{7\ d.f.}$ value of 14.067. Again, the lower calculated value will not permit the rejection of the hypothesis that the residuals are normally distributed.

An example will best show how probabilities can be associated with regression estimates. Suppose in month 14 from the contract baseline in the test project, the manager would like to know the probability of a total project cost greater than $500,000,000. Also, suppose he would desire to know the probability of an overrun of the present contract value, which is, for example, about $347,000,000. The contractor's estimate for this month is seen from Table XXIII to be $348,582,000.

First, these dollar figures are converted into the terms of the ratio, Y, by equation (3.1) which says

$$Y = \frac{AC - CE}{AC}$$

For the first case,

$$Y = \frac{500,000,000 - 348,582,000}{500,000,000} = 0.3028$$

and for the second,

$$Y = \frac{347,000,000 - 348,582,000}{347,000,000} = -0.00456$$

Figure 6 shows a normal distribution about the regression estimate, RE, of Y having a mean of RE and a standard deviation of $(0.00957)^{1/2} = 0.0978$. The 0.00957 value is the mean square error term for residuals in Regression II. The shaded portion indicates the probability of a total cost greater than a given amount, x.

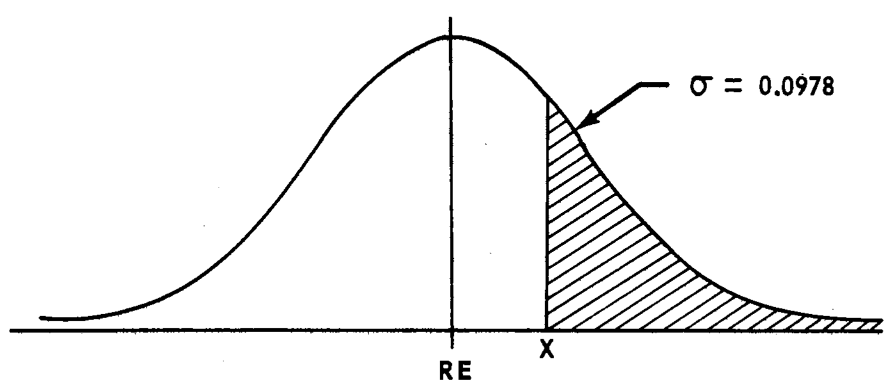

Figure 6. Probability of Given Total Cost

The area under the curve for the first case is found by use of the normal deviate as follows:

$$z = \frac{0.3028 - 0.2271}{0.0978} = 0.774$$

$$P(z > 0.774) = 0.2194 = 21.94\% .$$

Thus, the probability of a total project cost greater than $500,000,000 based on the regression estimate of month 14 is about 21.94 percent.

For the second situation, the normal deviate is

$$z = \frac{-0.00456 - 0.2271}{0.0978} = -2.37$$

$$P(z > -2.37) = 1 - P(z > 2.37) = 1 - 0.0089 = 0.9911 = 99.11\%.$$

Thus, the probability of an overrun of the present contract value, $347,000,000, is about 99.11 percent, again based on the regression estimate of month 14.

Although the model does not predict total actual cost amounts with great precision, it nontheless provides an excellent trend of total cost early in the life cycle of the project. It also permits the association of probabilities with given dollar values of total cost. This information in these two forms can be extremely valuable to the project manager and is a great improvement over the present cost information he has available to him, especially in the early months of the contract.

The study hypothesis is therefore accepted since the model is considered to have adequate trend prediction capability in the early months, since the prediction is dependent on the contractor's estimate adjusted by associated contract parameters (the independent variables), and since the Value Index, a measure of contractor performance, is included in one or more of these parameters.

CHAPTER V

CONCLUSIONS

General Remarks

The cost estimates of government research and development procurement contracts generally fall short of the actual costs finally incurred. Early cost estimates for major hardware articles in technologically-difficult, long-term R&D projects, such as launch vehicle development, are likely to be low by at least a factor of two or three.

If the government project manager is to exercise control over the resources of the project for which he is responsible, he must have tools available to determine if the contractor is proceeding toward the contract objectives as planned within established constraints. He must be advised of deviations from plan and trends that may suggest corrective action. When the contract which he manages is of long duration, perhaps even three to five years or more, an indication early in the project life-cycle that the contract cost will likely be much greater than expected can be of unquestioned value to the project manager. With this information, he may investigate the resource trade-offs he has available in order to realign the project costs with original plans, or he may re-evaluate the project objectives in terms of the predicted higher costs, and establish new plans.

Various management information systems have been developed to collect and present planning and control information to the project manager. Reporting requirements to support these systems have grown to the extent of concern from both government and industry management.

Two cost prediction systems have been discussed and evaluated in this investigation, principally for two reasons: (1) to indicate the detail, expense, and difficulties involved in implementing the systems, including the need for a supporting PERT system, and (2) to understand the Value of Work Performed calculation, a widely-accepted concept for measuring the contractor's cost and schedule performance.

A third and more recent philosophy of contract reporting was discussed to indicate the trend toward less detail and fewer constraints on the contractor in selecting systems and techniques used for internal company management. This freedom permits the government project manager to use specified summary level information from any supporting contractor systems to measure the performance of the contractor and predict total program cost trends.

This investigation has attempted to make use of the summary level information which is already being reported to the government, thus creating no requirements for additional data. By using this data, which include the contractor's own estimate of the total project cost, one can predict trends of cost for long duration projects in the early phases of hardware systems development. Included as one of the parameters of prediction was an index of contractor performance, based on a much simplified calculation of the of the Value of Work Performed, not dependent on a supporting PERT system, but theoretically equivalent to calculations of present systems.

Multiple regression analysis was used to establish the predictive model. A highly significant regression resulted which provides much improved predictions of early cost trends as compared to the contractor's estimate. A simple procedure was also described for assigning probabilities to any specified total cost prediction based on the appropriate regression estimate. This procedure provides the project manager with valuable information for managing the project resources: (1) an index of contractor performance simply calculated, (2) a prediction of total project cost, and (3) the probability of total costs over or under any given amount.

It is not claimed that the model developed in this investigation will apply to all research and development contracts, regardless of scope and objectives. There is no reason to doubt, however, that the regression methods employed in the second approach to problem solution in this study constitute a reasonable procedure for investigating available information from any R&D contract situation and using it to predict future cost trends.

Any user of the model developed here, or even the methods employed, must keep in mind that such a model requires periodic updating. This is true simply because of the dynamic nature of advanced technological research and development projects. However, it is not a difficult matter to check the validity of the model or the current accuracy of its coefficients with updated historical data.

Although the most obvious benefit of this investigation is the resulting simple and practical prediction model, a valuable by-product was also derived. Through isolation of some of the variables that affect the variation between the contractor's cost and actual costs, a broader insight has been developed into the overall management process of the research and development situation.

Proposals for Future Investigation

One of the merits of a systematic method of model derivation lies in the possibility it offers for future refinement with more complete data and even in the experience gained from use of the current model.

One refinement would be the possible inclusion of qualitative variables which can easily be handled in regression analysis. The referenced cost study from Rand Corporation attempted to evaluate the degree of technological advancement or extension of the state-of-the-art within a particular contract; there are others which would be potential variables.

The extension of the methods used here to internal contractor operations would be of interest. Future studies might well investigate the application of these methods to levels of cost consideration lower than the total contract cost, such as organizational or functional element levels.

The possibility of developing a similar model that is not dependent on the contractor's estimate of total cost should also be considered. Although there was not a constant variation in the contractor's estimate and the regression estimate, it is nonetheless obvious that the pattern of the regression estimate follows, to some degree, that of the contractor's estimate. It would be possible to develop a model which predicted total cost based on the original project budget adjusted by the same independent variables considered in this study.

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APPENDIXES

FOREWORD

Brief descriptions of the input, output, and calculations performed in the three programs written to support this investigation are included as follows:

Appendix A — "The Predicted Cost Program."

Appendix B — "The Ratio Program."

Appendix D — "The Test Program."

The Procedure Division for each of these programs is also included. The three programs were written in COBOL and run on the UNIVAC 1108 computer.

Appendix C contains the tabulated values calculated for Regression I and Regression II.

APPENDIX A

THE PREDICTED COST PROGRAM

THE PREDICTED COST PROGRAM

The "Predicted Cost Program" was written to perform the following calculations:

$$S.I. = MS\text{-}A/MS\text{-}S \quad (2.1)$$

$$C.I. = PC/AC \quad (2.2)$$

$$V.I. = (C.I.)(S.I.) \quad (2.3)$$

$$PRC = CE/V.I. \quad (2.8)$$

Input to the program for each project included:

1. Project code.
2. Cumulative count of milestones scheduled for each month (MS-S).
3. Cumulative count of milestones accomplished for each month (MS-A).
4. Cumulative cost planned for each month (PC).
5. Cumulative actual cost for each month (AC).
6. The contractor's estimate of project cost (CE) as of each month.

A listing of the Procedure Division of the COBOL program follows.

```
PROCEDURE DIVISION.
PAR-G.
    OPEN INPUT DATA-FILE, OUTPUT ANSWER-FILE.
PAR-1.
    READ DATA-FILE INTO INFO-REC  AT END GO TO END-ROU.
    ADD 1 TO CARD-CT.
    IF PROJ-CODE GREATER THAN PROJ-ID NEXT SENTENCE
         ELSE GO TO PAR-3.
ZEE.
    MOVE 0 TO FY68-PROJ, PROJ-68, FC-68, FIS-68, FIS-68-P.
    ADD 1 TO PROJ-ID.
    IF PROJ-CODE EQUAL 1 MOVE ' TABLE VI ' TO TITLE-1 ELSE
    IF PROJ-CODE EQUAL 2 MOVE ' TABLE VII' TO TITLE-1 ELSE
    IF PROJ-CODE EQUAL 3 MOVE 'TABLE VIII' TO TITLE-1 ELSE
    IF PROJ-CODE EQUAL 4 MOVE ' TABLE IX ' TO TITLE-1.
    WRITE LINE-IMAGE FROM HEAD-1  AFTER 63.
    IF PROJ-CODE EQUAL 1 MOVE 'A' TO PROJ-OUT ELSE IF
    PROJ-CODE EQUAL 2 MOVE 'B' TO PROJ-OUT  ELSE IF
    PROJ-CODE EQUAL 3 MOVE 'C' TO PROJ-OUT ELSE IF
    PROJ-CODE EQUAL 4 MOVE 'D' TO PROJ-OUT.
    WRITE LINE-IMAGE FROM HEAD-2  AFTER 3.
    WRITE LINE-IMAGE FROM HEAD-3  AFTER 3.
    WRITE LINE-IMAGE FROM HEAD-4  AFTER 1.
    MOVE 2 TO XYZ.
PAR-3.
    DIVIDE MS-SCHED INTO MS-ACCOM GIVING S-INDEX ROUNDED
    ON SIZE ERROR MOVE ZERO TO S-INDEX.
    DIVIDE CUM-ACTUAL INTO CUM-PLAN GIVING C-INDEX ROUNDED
    ON SIZE ERROR MOVE ZERO TO C-INDEX.
    MULTIPLY S-INDEX BY C-INDEX GIVING V-INDEX ROUNDED
      ON SIZE ERROR MOVE 99.999 TO V-INDEX.
PAR-33.
    DIVIDE V-INDEX INTO FY65-PROJ GIVING FC-65 ROUNDED
    ON SIZE ERROR MOVE ZERO TO FC-65.
    DIVIDE V-INDEX INTO FY66-PROJ GIVING FC-66 ROUNDED
    ON SIZE ERROR MOVE ZERO TO FC-66.
    DIVIDE V-INDEX INTO FY67-PROJ GIVING FC-67 ROUNDED
    ON SIZE ERROR MOVE ZERO TO FC-67.
    DIVIDE V-INDEX INTO FY68-PROJ GIVING FC-68 ROUNDED
    ON SIZE ERROR MOVE ZERO TO FC-68.
    IF FC-65 NOT EQUAL ZERO MOVE FC-65 TO FIS-65.
    IF FC-66 NOT EQUAL ZERO MOVE FC-66 TO FIS-66.
    IF FC-67 NOT EQUAL ZERO MOVE FC-67 TO FIS-67.
    IF FC-68 NOT EQUAL ZERO MOVE FC-68 TO FIS-68.
```

```
    ADD FIS-65  FIS-66  FIS-67  FIS-68 GIVING FC-TOT
      ON SIZE ERROR MOVE 9999999 TO FC-TOT.
    MOVE CARD-CT TO MO-OUT.
    MOVE C-INDEX TO CEX-OUT.
    MOVE V-INDEX TO VEX-OUT.
    MOVE S-INDEX TO SEX-OUT.
    MOVE FC-TOT TO FCAS-TOT.
    IF PROJ-CODE EQUAL 1 MOVE 506759 TO AC-OUT.
    IF PROJ-CODE EQUAL 2 MOVE 801832 TO AC-OUT.
    IF PROJ-CODE EQUAL 3 MOVE 463979 TO AC-OUT.
    IF PROJ-CODE EQUAL 4 MOVE 124071 TO AC-OUT.
    IF CARD-CT GREATER 1 MOVE ZERO TO AC-OUT.
    WRITE LINE-IMAGE FROM REC-OUT AFTER XYZ.
    MOVE 1 TO XYZ.
    IF CARD-CT EQUAL 42 MOVE ZERO TO CARD-CT.
    GO TO PAR-1.
END-ROU.
    CLOSE DATA-FILE, ANSWER-FILE.
    STOP RUN.
```

APPENDIX B

THE RATIO PROGRAM

THE RATIO PROGRAM

The "Ratio Program" was written to perform the following calculations:

$$Y = AC - CE/AC \qquad (3.1)$$

$$C.V. = (\text{Present } C.V. - \text{Baseline } C.V.)/\text{Baseline } C.V. \qquad (3.3)$$

Input to the program for each project included:

1. Project code.
2. Actual total project cost (AC).
3. The contractor's estimate of project cost (CE) as of each month.
4. Baseline contract value.
5. Present contract value as of each month.

A listing of the Procedure Division of the COBOL program follows.

```
PROCEDURE DIVISION.
PAR-G.
    OPEN INPUT DATA-FILE, OUTPUT ANSWER-FILE.
PAR-Q.
    READ DATA-FILE INTO ACT-REC AT END GO TO END-ROU.
PAR-X.
    IF PROJ-CO EQUAL 1 MOVE '  TABLE X ' TO TITLE-1 ELSE
    IF PROJ-CO EQUAL 2 MOVE ' TABLE XI ' TO TITLE-1 ELSE
    IF PROJ-CO EQUAL 3 MOVE ' TABLE XII' TO TITLE-1 ELSE
    IF PROJ-CO EQUAL 4 MOVE 'TABLE XIII' TO TITLE-1.
    WRITE LINE-IMAGE FROM HEAD-1 AFTER 63.
    IF PROJ-CO   EQUAL 1 MOVE 'A' TO PROG-OUT ELSE
    IF PROJ-CO   EQUAL 2 MOVE 'B' TO PROG-OUT ELSE
    IF PROJ-CO   EQUAL 3 MOVE 'C' TO PROG-OUT ELSE
    IF PROJ-CO   EQUAL 4 MOVE 'D' TO PROG-OUT.
    WRITE LINE-IMAGE FROM HEAD-2 AFTER 3.
    WRITE LINE-IMAGE FROM HEAD-3 AFTER 3.
    WRITE LINE-IMAGE FROM HEAD-4 AFTER 1.
    WRITE LINE-IMAGE FROM HEAD-5 AFTER 1.
    PERFORM PAR-1 41 TIMES.
PAR-1.
    READ DATA-FILE INTO INFO-REC  AT END GO TO END-ROU.
    SUBTRACT FY68-PROJ FROM ACT-68   GIVING DIFF
      ON SIZE ERROR MOVE -9999999 TO DIFF.
    DIVIDE ACT-68 INTO DIFF GIVING RA-68 ROUNDED.
    SUBTRACT CON-VAL FROM CV-OR      GIVING CON-CHG
      ON SIZE ERROR MOVE 9999999 TO CON-CHG.
    DIVIDE CV-OR      INTO CON-CHG GIVING PCENT ROUNDED.
    IF FY65-PROJ NOT EQUAL ZERO MOVE FY65-PROJ TO CE-65.
    IF FY66-PROJ NOT EQUAL ZERO MOVE FY66-PROJ TO CE-66.
    IF FY67-PROJ NOT EQUAL ZERO MOVE FY67-PROJ TO CE-67.
    MOVE FY68-PROJ TO CE-68.
    ADD CE-65 CE-66 CE-67 CE-68 GIVING CE-TOT.
    SUBTRACT CE-TOT FROM ACT-TOT GIVING TOT-DIFF
      ON SIZE ERROR MOVE -999999999 TO TOT-DIFF.
    DIVIDE ACT-TOT INTO TOT-DIFF GIVING RA-TOT ROUNDED.
    ADD 1 TO MUNTH.
    MOVE MUNTH TO MO-OUT.
    MOVE PCENT TO CV-CHG.
    MOVE RA-TOT TO RACT-TOT.
    WRITE LINE-IMAGE FROM OUT-PUT AFTER 1.
PAR-2.
    MOVE ZERO TO MUNTH.
    GO TO PAR-Q.
END-ROU.
    CLOSE DATA-FILE, ANSWER-FILE.
    STOP RUN.
```

APPENDIX C

THE NONSIMPLE MULTIPLE REGRESSION PROGRAM

REGRESSION I

PREDICTED VS ACTUAL RESULTS

RUN NO.	ACTUAL	PREDICTED	DEVIATION
1	.25260	.30369	-.05109
2	.24810	.31417	-.06607
3	.26980	.29676	-.02696
4	.26550	.31067	-.04517
5	.25990	.29826	-.03836
6	.11330	.32441	-.21111
7	.12660	.30952	-.18292
8	.12040	.30940	-.18900
9	.10340	.29782	-.19442
10	.08630	.19035	-.10405
11	-.06890	.20931	-.27821
12	-.12230	.22049	-.34279
13	-.10840	.08650	-.19490
14	-.12840	.09621	-.22461
15	-.12530	.13391	-.25921
16	-.11480	.14167	-.25647
17	-.13300	.07366	-.20666
18	-.12920	.11039	-.23959
19	-.12310	.10351	-.22661
20	-.07050	.06712	-.13762
21	-.07150	.02791	-.09941
22	-.06580	.00970	-.07550
23	-.15270	.01672	-.16942
24	-.14680	.01042	-.15722
25	-.13830	.00454	-.14284
26	-.12600	-.00198	-.12402
27	-.12480	.00551	-.13031
28	-.11500	.04753	-.16253
29	-.09010	.05590	-.14600
30	-.08720	.05137	-.13857
31	-.07810	.03021	-.10831
32	-.07380	-.02465	-.04915
33	-.07650	-.05756	-.01894
34	-.06720	-.07879	.01159
35	-.05210	-.08283	.03073
36	-.05170	-.13761	.08591
37	-.04550	-.12371	.07821
38	-.03680	-.09993	.06313
39	-.02860	-.07702	.04842
40	-.02080	-.02463	.00383
41	-.01560	-.07482	.05922
42	.00000	-.08358	.08358
43	.54350	.32496	.21854
44	.53980	.32971	.21009
45	.50860	.31661	.19199
46	.50810	.33409	.17401
47	.51120	.30866	.20254
48	.47020	.32775	.14245
49	.47260	.30713	.16547
50	.47180	.30605	.16575

PREDICTED VS ACTUAL RESULTS

RUN NO.	ACTUAL	PREDICTED	DEVIATION
51	.46540	.29067	.17473
52	.46340	.18477	.27863
53	.46080	.19366	.26714
54	.45380	.20439	.24941
55	.44380	.06176	.38204
56	.43610	.07239	.36371
57	.08600	.11992	-.03392
58	.08540	.13086	-.04546
59	.04940	.06398	-.01458
60	.05090	.10291	-.05201
61	.05400	.09516	-.04116
62	.05590	.05733	-.00143
63	.04920	.01686	.03234
64	.05530	-.00552	.06082
65	.04850	.00938	.03912
66	.04490	.00363	.04127
67	.04950	-.00465	.05415
68	.04580	-.01062	.05642
69	.04740	-.00315	.05055
70	.04780	.03453	.01327
71	.03030	.04494	-.01464
72	.03310	.03702	-.00392
73	.03640	.01785	.01855
74	-.02750	-.03407	.00657
75	-.02730	-.07088	.04358
76	-.02510	-.07094	.04584
77	-.02260	-.07767	.05507
78	-.00610	-.06263	.05653
79	-.00460	-.05539	.05079
80	-.00370	-.03200	.02830
81	-.00360	-.00300	-.00060
82	-.00180	.04814	-.04994
83	-.00050	-.00167	.00117
84	-.00030	-.00845	.00815
85	.51600	.40009	.11591
86	.52340	.41517	.10823
87	.53270	.41510	.11760
88	.53740	.41334	.12406
89	.54060	.37921	.16139
90	.33720	.37749	-.04029
91	.34120	.35555	-.01435
92	.34570	.36934	-.02364
93	.24860	.35724	-.10864
94	.25130	.24899	.00231
95	.24460	.24369	.00091
96	.14010	.24838	-.10828
97	.15860	.11853	.04007
98	.15180	.13021	.02159
99	.14320	.15677	-.01357
100	.14340	.15697	-.01357
101	.05700	.08580	-.02880

PREDICTED VS ACTUAL RESULTS

RUN NO.	ACTUAL	PREDICTED	DEVIATION
102	.05940	.12317	-.06377
103	.05940	.11168	-.05228
104	.03380	.07459	-.04079
105	.03320	.03958	-.00638
106	.02880	.01668	.01212
107	.01950	.01907	.00043
108	.01270	.00817	.00453
109	.01900	.00550	.01350
110	.01710	-.00256	.01966
111	.01130	.00423	.00707
112	.00720	.03953	-.03233
113	.00670	.04824	-.04154
114	.00490	.03870	-.03380
115	.00490	.01924	-.01434
116	-.03220	-.03392	.00172
117	-.02970	-.06811	.03841
118	-.02950	-.08909	.05959
119	-.01980	-.09575	.07595
120	-.02630	-.14650	.12020
121	-.03780	-.14831	.11051
122	-.03240	-.12514	.09274
123	-.00620	-.10050	.09430
124	-.00750	-.04826	.04076
125	-.00840	-.09861	.09021
126	.00000	-.10488	.10488

REGRESSION II

PREDICTED VS ACTUAL RESULTS

RUN NO.	ACTUAL	PREDICTED	DEVIATION
1	.25260	.40743	-.15483
2	.24810	.37224	-.12414
3	.26980	.35925	-.08945
4	.26550	.38360	-.11810
5	.25990	.32034	-.06044
6	.11330	.27352	-.16022
7	.12660	.23656	-.10996
8	.12040	.21434	-.09394
9	.10340	.19892	-.09552
10	.08630	.18618	-.09988
11	-.06890	.22889	-.29779
12	-.12230	.16858	-.29088
13	-.10840	.07446	-.18286
14	-.12840	.03659	-.16499
15	-.12530	.01713	-.14243
16	-.11480	.00492	-.11972
17	-.13300	.00882	-.14182
18	-.12920	.00424	-.13344
19	-.12310	-.00789	-.11521
20	-.07050	-.02196	-.04854
21	-.07150	-.01245	-.05905
22	-.06580	-.04648	-.01932
23	-.15270	-.04830	-.10440
24	-.14680	-.05864	-.08816
25	-.13830	-.06942	-.06888
26	-.12600	-.07705	-.04895
27	-.12480	-.07771	-.04709
28	-.11500	-.09554	-.01946
29	-.09010	-.09549	.00539
30	-.08720	-.09927	.01207
31	-.07810	-.09671	.01861
32	-.07380	-.08545	.01165
33	-.07650	-.08442	.00792
34	-.06720	-.07850	.01130
35	-.05210	-.07007	.01797
36	-.05170	-.06144	.00974
37	-.04550	-.04464	-.00086
38	-.03680	-.02783	-.00897
39	-.02860	-.01085	-.01775
40	-.02080	.00604	-.02684

PREDICTED VS ACTUAL RESULTS

RUN NO.	ACTUAL	PREDICTED	DEVIATION
41	-.01560	.02639	-.04199
42	.00000	.04167	-.04167
43	.54350	.37795	.16555
44	.53980	.35456	.18524
45	.50860	.37795	.13065
46	.50810	.38757	.12053
47	.51120	.38522	.12598
48	.47020	.38127	.08893
49	.47260	.37311	.09949
50	.47180	.29718	.17462
51	.46540	.34484	.12056
52	.46340	.28830	.17510
53	.46080	.26530	.19550
54	.45380	.30016	.15364
55	.44380	.29449	.14931
56	.43610	.24199	.19411
57	.08600	.12885	-.04285
58	.08540	.12116	-.03576
59	.04940	.10838	-.05898
60	.05090	.07875	-.02785
61	.05400	.07412	-.02012
62	.05590	.07235	-.01645
63	.04920	.08754	-.03834
64	.05530	.07634	-.02104
65	.04850	.07370	-.02520
66	.04490	.04613	-.00123
67	.04950	.05268	-.00318
68	.04580	.03194	.01386
69	.04740	.03075	.01665
70	.04780	.02628	.02152
71	.03030	.03323	-.00293
72	.03310	.03814	-.00504
73	.03640	-.00122	.03762
74	-.02750	.02159	-.04909
75	-.02730	.01607	-.04337
76	-.02510	.02975	-.05485
77	-.02260	.02211	-.04471
78	-.00610	-.03741	.03131
79	-.00460	.03034	-.03494
80	-.00370	-.00069	-.00301
81	-.00360	-.02712	.02352

PREDICTED VS ACTUAL RESULTS

RUN NO.	ACTUAL	PREDICTED	DEVIATION
82	-.00180	.13521	-.13701
83	-.00050	-.06373	.06323
84	-.00030	-.07786	.07756
85	.51600	.50898	.00702
86	.52340	.54001	-.01661
87	.53270	.58521	-.05251
88	.53740	.45830	.07910
89	.54060	.41911	.12149
90	.33720	.32071	.01649
91	.34120	.31980	.02140
92	.34570	.37958	-.03388
93	.24860	.35996	-.11136
94	.25130	.41438	-.16308
95	.24460	.28466	-.04006
96	.14010	.07977	.06033
97	.15860	.11089	.04771
98	.15180	.11703	.03477
99	.14320	.09590	.04730
100	.14340	.03531	.10809
101	.05700	-.03537	.09237
102	.05940	-.04319	.10259
103	.05940	-.03214	.09154
104	.03380	-.07083	.10463
105	.03320	-.09494	.12814
106	.02880	-.10546	.13426
107	.01950	-.06090	.08040
108	.01270	-.04580	.05850
109	.01900	-.07434	.09334
110	.01710	-.07638	.09348
111	.01130	-.07381	.08511
112	.00720	-.06379	.07099
113	.00670	-.06840	.07510
114	.00490	-.06102	.06592
115	.00490	-.06813	.07303
116	-.03220	-.06624	.03404
117	-.02970	-.07383	.04413
118	-.02950	-.07291	.04341
119	-.01980	-.07736	.05756
120	-.02630	-.07718	.05088
121	-.03780	-.00534	-.03246
122	-.03240	.00468	-.03708
123	-.00620	.00541	-.01161
124	-.00750	.01619	-.02369
125	-.00840	.01789	-.02629
126	.00000	.03014	-.03014

APPENDIX D

THE TEST PROGRAM

THE TEST PROGRAM

The "Test Program" was written to calculate the ratio, Y, for the test case, Project "C," based on the Regression II equation (Table XX). It compared this ratio with the actual ratio and printed the deviation between the two. Finally, the program calculated the predicted actual cost, equation (3.2), and compared it with the actual cost of the project.

Input to the program included:

1. Values for C. V. — (X_1).
2. Values for V. I. — (X_2).
3. Values for W. I. — (X_3).
4. Values for T. R. — (X_4).
5. The actual ratio, Y, for each month.
6. The contractor's estimate (CE) as of each month.
7. The total actual project cost (AC).

A listing of the Procedure Division of the COBOL program follows.

```
PROCEDURE DIVISION.
PAR-A.
    OPEN INPUT DATA-FILE, OUTPUT ANSWER-FILE.
    WRITE LINE-IMAGE FROM HEAD-A AFTER ADVANCING 63 LINES.
    WRITE LINE-IMAGE FROM HEAD-1 AFTER ADVANCING  2 LINES.
    WRITE LINE-IMAGE FROM HEAD-2 AFTER ADVANCING  2 LINES.
    WRITE LINE-IMAGE FROM HEAD-3 AFTER ADVANCING  1 LINE.
    MOVE 2 TO LR.
PAR-B.
    READ DATA-FILE INTO INFO-REC  AT END GO TO END-ROU.
PAR-C.
    COMPUTE RATIO ROUNDED = (5.1367 * XONE) -
    (.0473 * XTHREE) - (.0615 * XONE * XONE) -
    (4.0225 * XONE * XTWO) - (.8053 * XONE * XTHREE) +
    (1.2567 * XONE * XFOUR) + (.2412 * XTWO * XTWO) +
    (.3635 * XTWO * XTHREE) - (1.7190 * XTWO * XFOUR) +
    (1.5067 * XFOUR * XFOUR) - .6316
      ON SIZE ERROR MOVE -9.9999 TO RATIO.
PAR-D.
    COMPUTE PRED-AC ROUNDED = CONT-EST / (1 - RATIO).
    SUBTRACT RATIO-IN FROM RATIO GIVING DEV
      ON SIZE ERROR MOVE -9.9999 TO DEV.
    MOVE RATIO TO CALC-RAT.
    MOVE MO TO MO-OUT.
    MOVE PRED-AC TO CALC-ACT.
    MOVE DEV TO DEV-OUT.
    MOVE ACTUALX TO ACT-OUT.
    MOVE RATIO-IN TO ACT-RAT.
    WRITE LINE-IMAGE FROM REC-OUT AFTER ADVANCING LR LINES.
    MOVE 1 TO LR.
    GO TO PAR-B.
END-ROU.
    CLOSE DATA-FILE, ANSWER-FILE.
    STOP RUN.
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VITA

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Candidate for the Degree of

Doctor of Philosophy

Thesis: A MODEL FOR PREDICTING COST TRENDS FOR R&D LAUNCH VEHICLE CONTRACTS

Major Field: Engineering

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