Utilization of Probabilistic Network Analysis in Planning Long-Range Engineering Projects

D. W. Swindle, Jr., E. H. Gift, F. M. Bustamante

Union Carbide Corporation - Nuclear Division*
Oak Ridge, Tennessee

*Operated under Contract W-7405 eng 26 with the U. S. Department of Energy

Abstract

The application of the GERT (Graphical Evaluation and Review Technique) probabilistic network analysis technique and the results obtained from a program analysis using GERT is discussed. A historical summary of decision analysis techniques leading to the development and application of GERT is included. Discussion is provided on the GERT methodology, study rationale, and results of an analysis examining the Receiving and Storage Task at the Oak Ridge National Laboratory. Long-range program planning advantages using GERT are identified and discussed as relates to the methodology's decision analysis capability.

INTRODUCTION

The planning and scheduling of long-range engineering programs in an area with many unknowns is a common problem faced by engineering management. Successful program planning with alternatives to compensate for uncertainties in funding and technology development requires a tool that can aid management in the establishment and evaluation of program plans and in keeping track of critical paths, financial projections, and milestones. This paper demonstrates the usefulness of the GERT (Graphical Evaluation and Review Technique) (1) in such planning by presenting results from its application to a nuclear systems research and development program currently in progress at the Oak Ridge National Laboratory. The program task analyzed and presented in this paper is a part of the CFRP's (Consolidated Fuel Reprocessing Program) effort to demonstrate and develop technology and systems for the reprocessing of spent fuel from advanced type reactors.

The specific program task investigated was the Receiving and Storage Task of the CFRP. This task was chosen as the evaluation model because the program development logic was well-structured and satisfied the requirements necessary for an effective analysis by the GERT methodology. Although the specific details of the Receiving and Storage Task plan are not necessary for this paper, it is important to note that the task plans were characterized by uncertainty in future activities and decisions that, in turn, direct the outcome of particular development projects. The task maintains parallel engineering research and/or development activities that, after satisfactory completion, focus on a probabilistic decision point that directs the future course of the engineering effort.

The evaluation of the Receiving and Storage Task was planned to generate information regarding task completion times, task cost to completion, and likelihood of completion by a specific schedule time. The evaluation required the preparation of a representative network logic diagram that was analyzed through the use of the modeling flexibility of the next-event computer simulation code, GERTS III-Z (2).

This paper provides a brief background summary of the decision analysis techniques leading to the development and application of GERT. It then discusses the methodology, study rationale, and results of the Receiving and Storage Task analysis. Further details of the analysis and the results obtained may be found in Reference 3.

HISTORICAL SUMMARY

To best appreciate the advantage of utilizing the GERTS III-Z technique for engineering project planning and management, it is desirable to examine some previous methods and modeling techniques that have been used as management aids. This summary includes an overview of each technique and its advantages and disadvantages before examining the GERT method in detail.

Near the turn of the century, the Gantt chart or Bar chart was developed. In this chart, each

CH1437-3/79/0569-0575$00.75 © 1979 IEEE
1979 Winter Simulation Conference

bar represents the beginning, duration, and end in time of some segment of the total of the activity to be performed. Together, the bars make up a schedule for the total task. However, as soon as the need for, and the development of, large-scale engineering systems or development projects came about, some fundamental weaknesses in the Bar chart as a management tool were revealed. Specifically the Bar chart's weaknesses are:

1. An inability to show interdependencies that exist between the various efforts represented by the bars;
2. An inflexibility that prevents it from easily reflecting slippage or changes in plans; and
3. An inability to reflect uncertainty in the duration times estimated for the various activities represented by the bar.

An important step forward occurred when the idea of milestone charts surfaced. This system provided a sequential listing of the various activities for a particular task. This innovation was important because it recognized the functional elements of a program task that reflected the work breakdown structure more accurately. The utilization of the milestone system proved quite effective and is still widely used. The limitations of the milestone charts are:

1. The lack of identifiable relationships between the milestones, and
2. The fact that the system does not allow for measuring the effect of activity changes or slippages, but merely has improved the reporting of them.

Even with these limitations, the milestone system was a considerable improvement in the evolution of network-based management planning. This system forced the need for early awareness and discipline at the engineering staff level, and it also forced a detailed, logical, sequential and event-oriented planning of the various segments of the program task.

This, in turn, facilitated the development of CPM (Critical Path Method) and PERT (Program Evaluation and Review Technique). The CPM utilizes an arrow-diagram technique developed from more detailed Bar charts that were job- or activity-oriented. Similarly, the PERT technique utilizes a network of arcs and nodes representing activities and milestones, respectively, which evolved from a combination of Bar charts and milestone charts. The PERT technique is heavily event-oriented or milestone-oriented, and has served management by assisting in schedule evaluation while the job is in progress. Using PERT analyses combined with CPM techniques, managers could analyze massive engineering programs with multiple and overlapping responsibility divided among the overseeing organizations.

Both PERT and CPM require:

1. Well-defined, deterministic projects; and
2. Relatively small uncertainty about task component activity behavior.

However, PERT and CPM have limitations also. Specifically, in determining the critical paths, statistical uncertainty of the activity duration times can alter, and has altered, the outcome of the critical path result (4). By performing similar PERT analyses of systems having statistical uncertainties, consistent underestimates of the mean time to project completion and an overestimate of the variance have been observed (4,5). Also, when analyzing research and development engineering projects, expenditure planning is often poorly estimated, with possible misdirection of funds. In this case, neither PERT or CPM is incapable of handling such a problem directly.

As a result of these limitations, researchers have developed GERT. Unlike PERT, this tool allows for probabilistic and decision analyses to be included in task or program evaluations.

METHODOLOGY

The GERT program utilized is the GERT version III-Z. GERTS III-Z is a simulation approach to the analysis and evaluation of stochastic networks. Based in part upon the GASP-IV simulation language (6), the code is a rather flexible and general purpose tool.

Although the essential methodology utilized in our analysis was the GERTS III-Z computer code, the actual analysis was done using a technique specifically developed for program management, PAF (Partitive Analytic Forecasting) (7). PAF has been developed to provide management aids in the following areas:

1. Definition of necessary steps in long-range development programs;
2. Clarification of the long-range program plans;
3. Identification of the limiting factors in the program development;
4. Investigation of the possible consequences of various funding strategies; and
5. Investigations of possible futures by utilization of scenarios.

The subsequent application of the methodology involves four major steps:

1. The determination of essential scientific, engineering, and administrative tasks, of potential means of accomplishment of these tasks, and of relationships between the diverse tasks and means;
2. The gathering of time, probability, and cost estimates from individuals directly involved in the research effort;

3. Computer simulations of possible development schemes; and

4. Analysis and evaluation of results.

As in GERTS III-Z, the modified code utilizes logic networks that describe the program plan and that represent future plans for the research and development effort. Logic networks, which were prepared as part of the above application, Steps 1 and 2, served as detailed control charts for the program manager before the process of simulation begins. Often these charts, by themselves, can provide the program manager with significant insight into program management through identification of cross impacts from within as well as from outside his own program. GERTS III-Z is utilized because the code can accommodate: (a) progress uncertainties, (b) cross-impact studies, (c) design network alterations, (d) credit for partially successful developments or experiments, (e) easy network alterations from one scenario to another, (f) cost analyses, (g) probabilistic time and cost data, and (h) risk analyses. By providing such versatility, several scenarios can be examined with a network that more closely models reality.

STUDY RATIONALE

The development effort modeled (i.e., the Receiving and Storage Task) was described in sufficient detail to include probabilistic, as well as deterministic, decision analysis. The task, which consists of seven subtask programs, has been modeled from two viewpoints. First, each of the subtasks was modeled as an independent program and assumed to function in an entirely smooth and orderly manner. This "ideal" case study served as the basis for identifying positions of delay and/or initial activities when evaluating the "base" case study. The base case analysis represented the second viewpoint from which the program task was evaluated. This case evaluation served to model the dependent relationships between the subtasks, including all subtask coordination and design integration activities. The results obtained from the base case analysis identified activity delay sources and critical activity levels within each subtask, as well as statistical measures of program completion, given constraints of time and financial resources.

Specifically, the immediate statistical results obtained from the analysis of the base case and the ideal scenario are found in three basic areas. These three areas are a comparison of the:

1. Likelihood of task (subtask) completion as a function of the time to completion;

2. Likelihood of task (subtask) completion as a function of the total task (subtask) cost to completion; and

3. Spending rate and likelihood of task (subtask) completion with time.

By correlating these results with established task milestones, ranges for projected annual spending activity for each fiscal year were prepared. Also, the likelihood of meeting desired milestone objectives, given current resource constraints (time and money), was determined.

The analysis of the base case scenario would be incomplete if there were no attempt to analyze the consequences of perturbations upon the system. The desired result is to identify activities which, if delayed, could lead to an eventual delay in completing the overall task, or individual subtask, by a given date.

In this study, six additional cases were analyzed that assessed the sensitivity of the probability estimates at all decision points in the control logic diagrams, and which also addressed cost and time restructuring for the original task plans.

RESULTS

The results obtained from the evaluation of the Receiving and Storage Task are the product of 1000 simulations for each subtask and 1500 simulations for the task as a whole. The reason for the difference in the number of simulations for the task and for the subtask is that for each case these numbers represent the required simulations to obtain consistent, stable statistical results. The results have been summarized by category, with the categories being: I. Milestones, II. Times and Constraints, III. Cost, and IV. Perturbation Analysis.

By category, the results were as follows:

I. MILESTONES

The initial milestones characterized by a June 1977 date in the task plans were met with no problem in scheduling or delaying activities. A second milestone set for a June 1982 accomplishment date was determined to have a likelihood of zero (0) of being met by all subtasks. Even when this milestone date was slipped by one year, its likelihood of attainment was still zero, due to uncertain scheduling activities in the then current logic plan.

II. TIMES AND CONSTRAINTS

The estimated likelihood of overall task completion by a given date is depicted graphically in Figure 1. As can be determined from the figure, a reasonable likelihood of completion (greater than 80%) requires, at a minimum, the expenditure of 1920 project days. This implies an 80% or greater likelihood of completing the overall task by October 1984. The minimum time for completion (having a near zero probability of attainment) was 1615 project days, or July 1983. The mean time for task completion (a 50% probability of attainment) was 1884 project days, or September 1984. A 100% probability of task completion could be expected in 2269 project days, or April 1986. These results are displayed in Table 1. Corresponding results were obtained for each individual subtask.

FIGURE 1

RECEIVING AND STORAGE TASK

(Likelihood of Task Completion as a Function of Time to Completion)

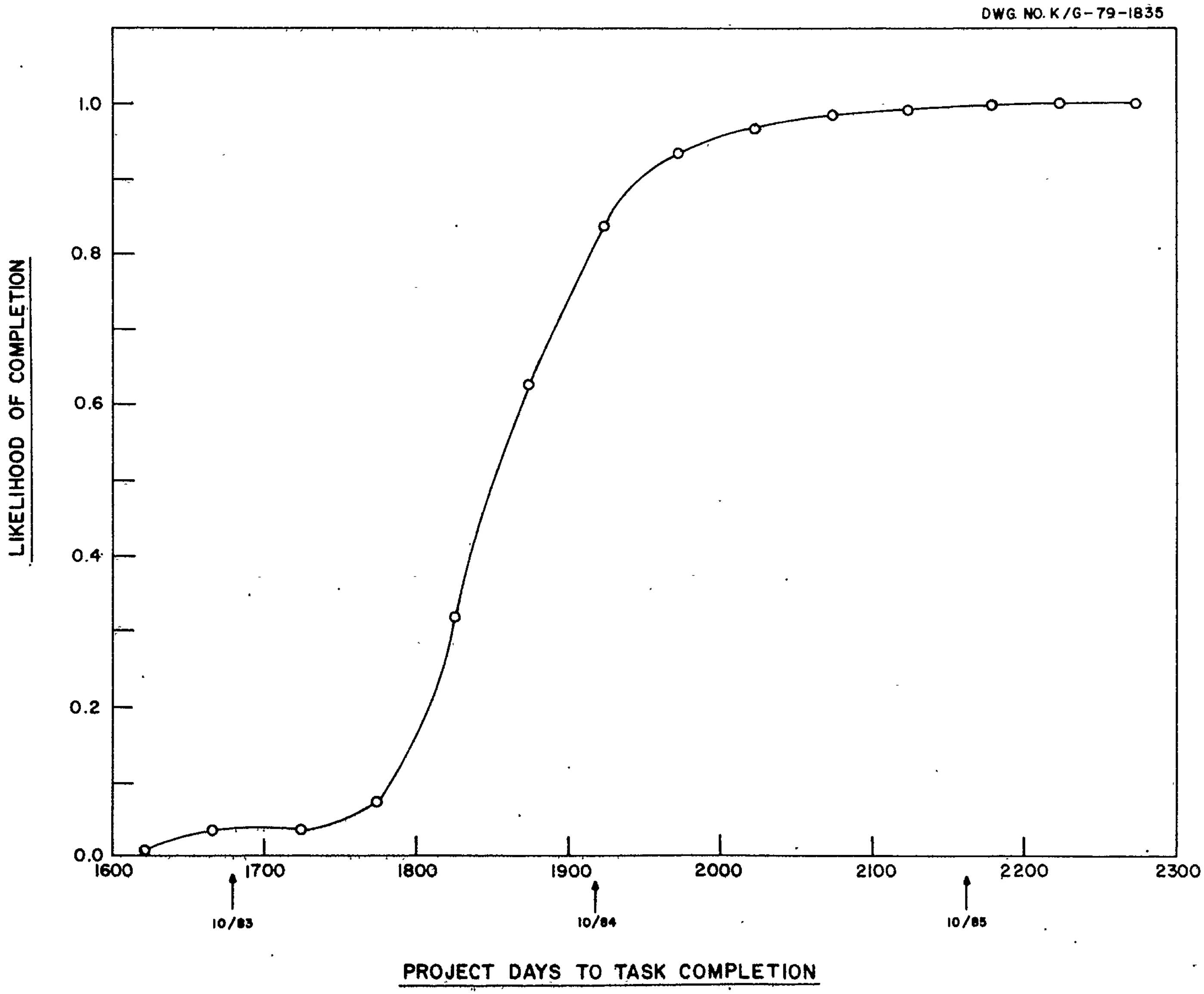


TABLE 1					
DATES TO TASK COMPLETION					
Minimum		Mean		Maximum	
Project Days	Calendar Date	Project Days	Calendar Date	Project Days	Calendar Date
1615	7/83	1884	9/84	2269	4/86

In addition, each of the seven component subtasks could be characterized by its importance in terms of being activities that could delay meeting anticipated objectives. It was found that of the seven subtasks, only two significantly affected the overall task completion time. This result provided the capability to establish priorities for manpower and expenditure utilization.

III. COSTS

The evaluation of the project costs and expenditure rate was carried out from two viewpoints — from the individual subtask level without administrative interaction and from the overall task viewpoint as the cumulative costs (including administrative costs) to completion. The subtask level costs are from the noninteractive (ideal) case analysis. The overall task costs are from the interactive, base case analysis. Using the base case analysis, the projected annual spending activity through fiscal 1984 is given in Table 2. From the consideration of the mean, the greatest fiscal activity is to occur from fiscal year 1979 through fiscal year 1982. The range of the cumulative task cost to completion with the median cost for the task is also important. In Table 3, the mean cost to task completion is shown to be $11,691,000 (in terms of 1977 dollars). Of interest is the correlation between the spending rate as a function of time and the likelihood of completion as a function of time. Shown in Figure 2, the minimum expenditure ranges from $9,471,800 to $13,250,000 before experiencing any likelihood of task completion. This cost range corresponds to 1615 project days.

TABLE 2

PROJECTED ANNUAL SPENDING ACTIVITY

FY	Calendar Dates	Cost ($ thousands) Minimum	Mean	Maximum
1977	10/76-9/77	1046.0	1046.1	1051.6
1978	10/77-9/78	789.3	861.6	963.0
1979	10/78-9/79	1835.5	2035.7	2376.8
1980	10/79-9/80	1622.6	1894.2	2217.9
1981	10/80-9/81	2170.9	2702.2	3285.6
1982	10/81-9/82	1326.4	1563.8	1917.9
1983	10/82-9/83	612.7	1140.9	1473.7
1984	10/83-9/84	68.5	418.5	1011.4

TABLE 3

CUMULATIVE COST TO TASK COMPLETION ($ thousands)

Minimum	Mean	Maximum
9,471.8	11,691.1	14,427.8

By tracing the curve for minimum expenditures, the likelihood of completion can be seen to increase rapidly. This follows the intuitive conclusion that with cumulative expenditures on the increase, the potential for task completion also rises. The most significant data from this collective plot are obtained using the left-indexed mean cost curve and right-indexed likelihood of completion curve. The likelihood of completing the task's objectives at a given time can be determined by selecting an expected level of expenditure and a date for completion. This information can be very valuable to assess budgetary cuts (or increases) and their overall impact on the program's development plans. Similar results were obtained for the individual subtasks.

IV. PERTURBATION ANALYSES

In general, for the perturbation effects tested, the overall measure of the task's likelihood of completion by a given date remained unaffected (except for the normal statistical fluctuations). The only exception to this general rule was found in the perturbations that affected one subtask. This exception was a result of longer average activity duration times that exceeded the already inherent delays identified in the base case analysis.

By measuring the likelihood of completion as a function of cumulative cost with completion for each run, the result is that, except for normal statistical fluctuations, no changes are noticed. This result confirms the fact that with only time delays incorporated in the perturbation runs, the costs, which remain the same, should accumulate in the same manner until project completion.

The final case studies conducted involved measuring the sensitivity of the estimates of the probabilities at all decision points in the control logic diagrams. The two measures involved varying the values of the probabilities by +10% and -10%, respectively. The +10% variance in probability estimates led to:

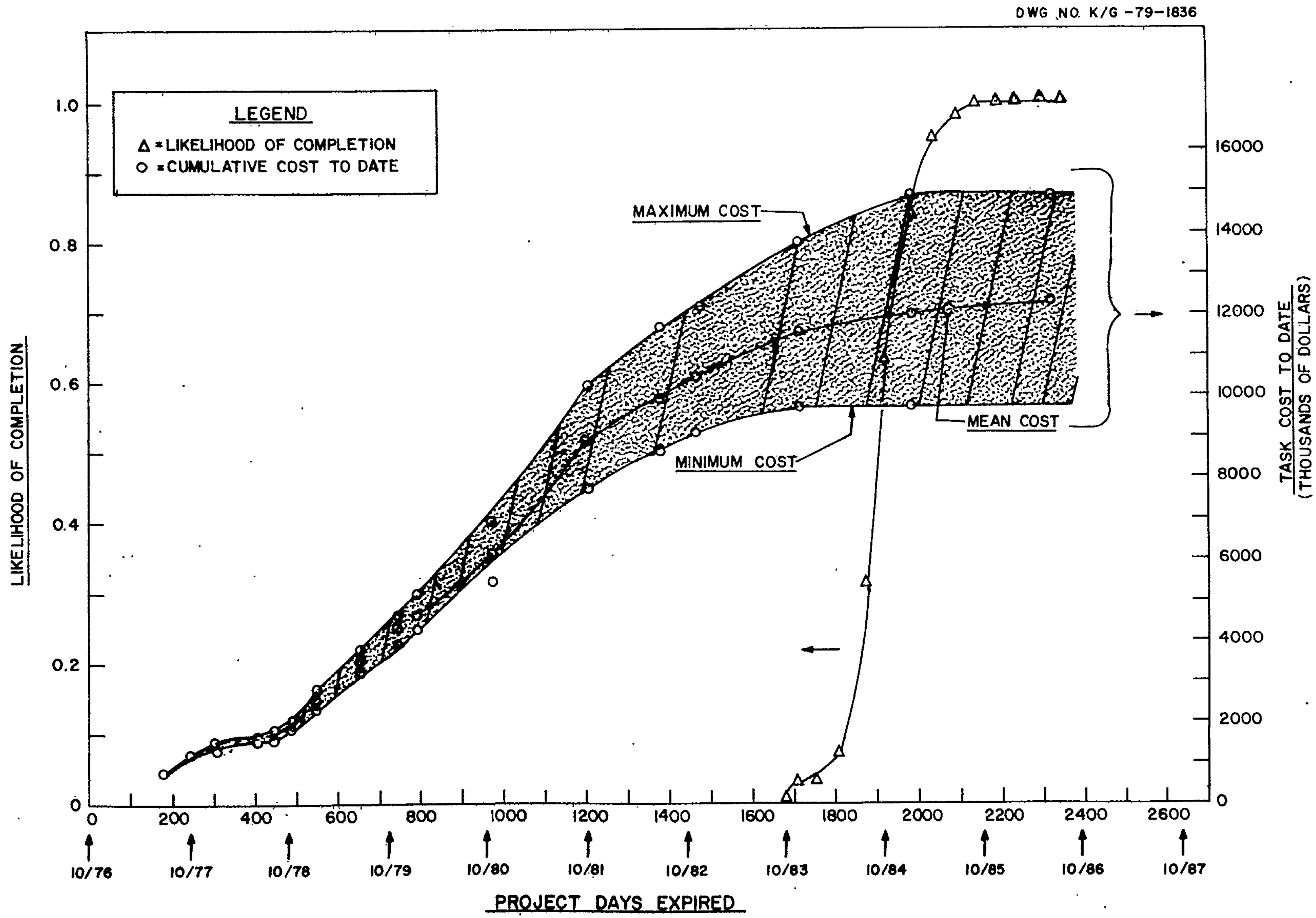
1. Reducing the likelihood for modification by 10%;
2. Reducing the likelihood for ending an activity level prior to full development by 10%; and
3. Increasing the likelihood for a successful Proof of Principle Test and detector development by 10%.

In general, these variances of the probability estimates should be to increase likelihood for

FIGURE 2

RECEIVING AND STORAGE TASK

(Comparison of Likelihood of Completion and Expenditure Activity with Time)



development, thus maximizing design confidence and reliability, but increasing cost and schedules.

For the case involving the negative variance on probability estimates (-10%), the inverse effect occurs. This procedure resulted in:

1. Increasing the likelihood for modification;
2. Increasing the likelihood for ending an activity level prior to full development; and
3. Decreasing the likelihood for a successful Proof of Principle Test and detector development.

Therefore the resulting effect, in general, should be to decrease the likelihood for development, thus minimizing design confidence and reliability for the case in consideration.

In actuality, the results of the case study (±10% variance in estimated probabilities) showed insensitivity to the changes with regard to the statistical variations. This is true, not only for the overall task analyses, but also for the subtask analyses.

CONCLUSIONS

The results of the GERT evaluations confirmed the estimated cost projection while providing a statistical cost range. Furthermore, the additional time required to complete the task plan as identified was recognized as normal, because no single activity had a success factor of one. It was recognized statistically that some things had to be "done over" at least once.

Now after more than a year of research and development effort, the actual program plans have been in very good agreement with what the evaluation predicted. The effort expended for this evaluation has been worthwhile. A valuable new program tool has been demonstrated that can aid management in directing and planning complex research and development engineering programs. In addition, future plans have resulted in development of a series of activities to examine and evaluate nearly all scheduled tasks in the CFRP.

BIBLIOGRAPHY

1. Pritsker, A. B., Burgess, R.R., "The GERT Simulation Programs: GERTS III, GERTS IIIQ, GERTS IIIC, and GERTS IIIR," Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

2. Pritsker, A. B., and Sigal, L. E., The GERTS III-Z User's Manual, Pritsker and Associates, Lafayette, Indiana, 1976.

3. Swindle, Jr., D. W., "A Probabilistic Network Analysis of the Advanced Fuel Recycle Program's Receiving and Storage Task," K/OP-247, Union Carbide Corporation, Oak Ridge, Tennessee, June 26, 1978.

4. Whitehouse, G. E., Systems Analysis and Design Using Network Techniques, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1973.

5. MacCrimmon, K. R. and Ryavec, C. A., "An Analytical Study of the PERT Assumptions," Operations Research, Vol. 12, pp. 16-37, 1964.

6. Pritsker, A. B., The GASP IV Simulation Language, John Wiley and Sons, New York, 1974.

7. Vanston, Jr., J. H., et al., "PAF--A New Probabilistic Computer-Based Technique for Technology Forecasting," Technological Forecasting and Social Change, Vol. 10, pp.239-258, (North Holland) Elsevier, 1977.