Simulation Model to Forecast Project Completion Time

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Abstract: Project cost is most sensitive to its schedule. The construction project environment comprising dynamic, uncertain, but predictable, variables such as weather, space congestion, workmen absenteeism, etc., is changing continuously, affecting activity durations. The reliability of project duration forecast can be enhanced by an explicit analysis to determine the variation in activity durations caused by the dynamic variables. A computer model is used to simulate the expected occurrence of the uncertainty variables. From the information that is collected normally for a progress update of the tactical plan and by simulating the project environment, the combined impact of the uncertainty variables is predicted for each progress period. By incorporating the combined impact in the duration estimates of each activity, the new activity duration distribution is generated. From these activity duration distributions, the probability of achieving the original project completion time and of completing the project at any other time is computed.

Introduction

A project is considered successful if it is completed within its scheduled duration and estimated cost. Sensitivity analysis (11) shows that the most critical parameter affecting cost is the project schedule. To keep the project on schedule, it is imperative for the project management to make an accurate forecast of project duration for establishing the pace of performance and also to revise it at regular intervals in view of the dynamic environment of the project.

A reliable forecast of the completion date is one of the major concerns of a scheduling engineer. This reliability is dependent upon the accuracy of the network logic, individual activity duration estimates, and various uncertainty variables in the project environment such as weather, productivity level, etc. During project implementation, many uncertain but predictable variables dynamically affect the activity duration. Currently, to forecast project duration, their impact is considered intuitively, and its effectiveness depends upon the skill of the scheduling engineer. For more reliable forecasts of project duration, it would be beneficial to develop a computer model that can simulate the expected occurrence of the uncertainty variables, explicitly analyze and quantify their combined impact, and incorporate it in the activity duration estimates. Such a model can generate additional management information, such as a criticality index for each activity, the need for a schedule revision, and level of sensitivity of an activity to specific uncertainty variables. This is expected

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to give the management an insight into the project schedule. Being forewarned, the management can take appropriate timely corrective action to keep the project on schedule.

This paper presents a model that meets this need and examines its working, applications and limitations.

Need for Realistic Forecast of Project Completion Time

As already stated, it is essential to have a reliable forecast of project completion time because of the following reasons:

1. Many studies have revealed that it is possible to make relatively greater percentage of recovery if the potential delay is recognized earlier in the life of a project. The potential recovery decreases as one proceeds through the project until a time is reached when recovery is no longer possible. The early indication of delay through a reliable forecast allows decisions to be made in a less hectic environment.
2. A delay in project completion can cause a cost escalation at least equal to the sum of inflation, overhead cost, and additional interest cost for the period. A realistic forecast gives a clear picture so alternative decisions involving time/cost tradeoffs can be taken.
3. In a production oriented project, the marketability of the product is affected if its arrival on the market is delayed. Any delay in projects relating to infrastructure facilities upsets the economic feasibility of the projects that depend on them. An awareness of the project status through reliable forecasts helps keep the project on schedule.

Project Environment

To estimate duration of an activity, the resources normally used on such activities, the work content of the activity and the average productivity on similar activities from historical record are considered. These estimates would hold, if during its life, the project environment remains the same as envisaged at the time of planning. But in real life, as the project progresses, its activities encounter many problems that may impinge upon their duration. The causes for these problems are mostly uncertain yet predictable variables that dynamically affect the activity durations. The assessment of their impact is a complex problem since the variables are dynamic and dependent on project conditions, location, and the time of year when the activity will be worked on. For example, a concreting activity is more susceptible to weather compared to activities such as interior drywall or indoor equipment installation.

Influenced by many dynamic variables, some activity durations deviate from the original estimate, thereby changing the critical path. Current scheduling practice does not include simulation of the expected project environment to evaluate corresponding impact of dynamic uncertainty variables on activity durations.

State of the Art

A project passes from the conceptual stage through the commissioning stage via a project cycle. The project cycle comprises planning and

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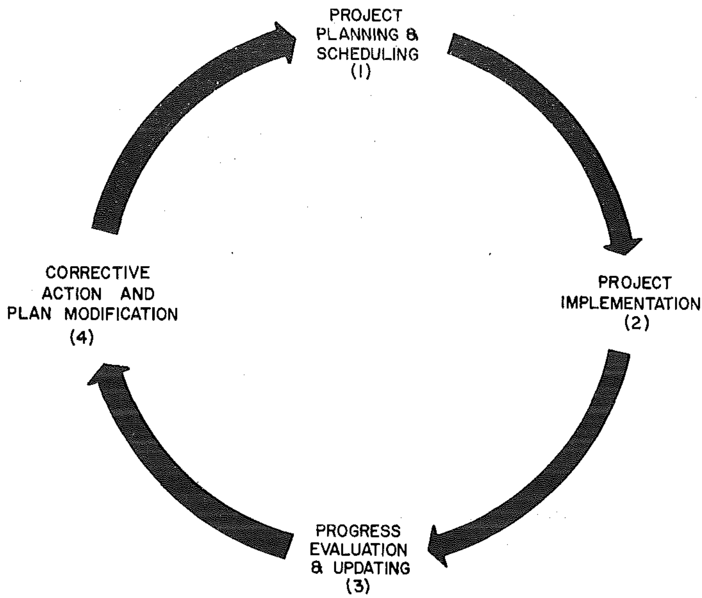

FIG. 1.—Project Cycle

scheduling, implementation, progress evaluation and updating, and corrective action and plan modification (2) as shown in Fig. 1.

During the planning stage, a strategic plan is prepared for the entire duration of a project. A tactical plan for 2–3 reporting periods is developed on a recurring basis. A provision is made in the form of a fictitious activity at the end of the strategic plan, with its duration equal to the contingency time that may be required in case of unforeseen occurrences. This contingency time accounts for the impact of the uncertainty variables. Activities at the tactical plan level are scheduled after intuitively incorporating the combined impact of the uncertainty variables. During project implementation, progress is monitored, and feedback is used to update the plan and prepare reports for progress evaluation. Management evaluates actual against planned progress, identifies causes of delay, takes corrective action, and, if necessary, revises the duration estimates of activities in progress and of those that are yet to start. In revising the activity durations, the influence of uncertainty variables is taken into account intuitively at best.

The strategic plan is revised only when the contingency time allowance is exhausted. The project cycle is repeated until the project is complete.

The reliability of activity duration estimates, project completion forecasts, and effectiveness of corrective measures, all depend on the adequate incorporation of the impact of the uncertainty variables. One specific uncertainty variable may influence a particular activity more than others. A knowledge of the sensitivity of the various activities to different uncertainty variables enables management to devote the required additional attention to them. Also, without knowledge of the criticality index, the project management cannot predict with confidence the activities that may not be critical originally but are likely to become critical later.

Suhanic (11), Parviz (10), Gates and Scarpa (6), and Baldwin (3) have studied the individual effect of some of the significant uncertainty variables. Halpin and Woodhead (7) have developed models to determine the combined impact of some of the major uncertainty variables for a classroom project management game, for use in mainframe computers. These models aimed at confronting the student with problems in a game environment similar to those actually encountered on the job site. Recently, some researchers have tried to extend the methods of project management games to make reliable forecasts of project completion time. However, the following deficiencies have been observed in the present state of the art:

1. Although the individual impact of some of the uncertainty variables over activity duration has been considered, only a start has been made to combine it. Models capable of incorporating the combined impact of the significant uncertainty variables in project scheduling do not exist.
2. Because changes in the project environment can be predicted with greater confidence for the shorter tactical plan period, it makes sense to treat it separately from the strategic plan while simulating the project environment. However, many conventional schedule updating procedures do not draw a distinction between tactical and strategic plans.
3. The adoption of a new methodology in the construction industry depends on its capability to enhance reliability of management information with least disturbance to the existing procedures. No attempt seems to have been made to develop a model that will produce more reliable project duration forecasts from the project progress data conventionally collected for schedule updating, while also incorporating the combined impact of the uncertainty variables. These deficiencies can be restated to pinpoint the problem.

Problem Statement

The project environment considered while estimating an activity duration at the planning stage does not remain static during its implementation. The intuitive consideration of the combined impact of the dynamic uncertainty variables many times fails to produce reliable project duration forecasts. The present scheduling and updating procedures do not perform any explicit analysis to generate the following information: (1) The expected variation in activity durations caused by the dynamic project environment; (2) the likelihood of an activity becoming critical under changed project environment; (3) the sensitivity of an activity duration to a specific uncertainty variable; and (4) a separate probability distribution for tactical and strategic plan completion time in preference to a deterministic estimate. This information can aid in effective implementation of the project. Thus, a computer model is necessary that simulates the dynamic uncertainty variables and incorporates their com-

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bined impact in the activity duration estimates for more reliable project completion forecasts at each progress review.

Objectives of Research

1. To select a set of significant uncertainty variables, study them in detail, and determine a suitable method for simulating their impact on the activity durations.
2. To determine through simulation, at each progress review, the combined impact of all uncertainty variables, incorporate it in the duration estimates of tactical plan activities, and obtain for each activity the duration distribution.
3. To determine from Monte-Carlo simulation the alternative tactical plan completion times.
4. To determine the alternative project completion times, using the strategic plan.
5. To predict the probability of achieving the original schedule from the distribution of project completion times.
6. To compute the sensitivity of activities to specific uncertainty variables.
7. To obtain the preceding management information from the progress data normally collected on site for periodical updates without disturbing the existing procedure that generates updated schedules for use by the field staff.

Variables Affecting Activity Duration

Some of the variables that cause uncertainty in activity duration estimates are: (1) Learning curve; (2) weather; (3) space congestion; (4) crew

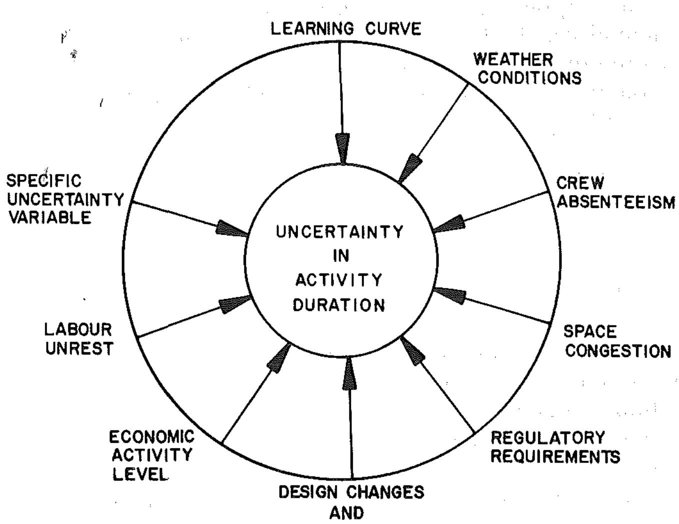

FIG. 2.—Significant Uncertainty Variables

absenteeism; (5) regulatory requirements; (6) design changes and rework; (7) economic activity level; (8) labor unrest; (9) crew interfacing; (10) project complexity; (11) foundation conditions; (12) design delta collection schedule; (13) drawing approval schedule; (14) inspection schedule; (15) ineffective supervision; (16) inefficient consultant; (17) building code; (18) transportation schedule; (19) construction materials delivery schedule; (20) legal problems; and (21) union problems.

Based on a literature survey and field experience, certain uncertainty variables are considered more significant (1) as shown in Fig. 2. The selection of variables is only to aid in explaining the concept; their selection must depend on the project under consideration. A provision exists to delete, add, or replace any of the variables.

Impact Considerations of Significant Uncertainty Variables

The following are qualitative and quantitative impact considerations of the significant uncertainty variables.

Learning Curve.—It is known that productivity in a job increases with experience and practice. The cumulative average time (CAT) to do a complex work varies exponentially and inversely as the number of repetitions increases. The total time required to construct any given number of units is the product of the number of units and the CAT per unit. The slope of the straight line relationship between the CAT and number of units increasing in geometrical progression is

$$S = \frac{\log r}{\log 2} \qquad (1)$$

where r = a constant representing the rate of decrease in time due to routine acquiring based on doubling the number of units.

Decremental constant is the percentage rate at which the CAT decreases as the number of repetitions increases. It is $r \times 100\%$.

For a large number of repetitions n, the relationship between S, n and CAT is given by

$$\mathrm{CAT} = n^s \qquad (2)$$

and $$S = \frac{\log \mathrm{CAT}}{\log n} \qquad (3)$$

Gates et al. (6) have reported separate decremental constants for building structures, individual construction elements requiring many operations to complete, construction elements with few operations fabricated on assembly-line basis, and building elements manufactured in a plant. While estimating activity duration for a project, the tendency seems to take average productivity figures from similar activities on several projects. Many deviations, such as variation in the competence of crews, break in an activity and its resumption later, resignation by some experienced crew, etc., are not considered. These deviations affect the decremental constant, resulting in variation in cumulative average time and, thus, in the activity duration estimate.

Weather.—The effect of natural environment strongly influences the progress of construction. The uncertainty in activity duration estimate due to weather is dependent upon the time of the year the activity is performed. Weather conditions affect labor productivity as well as activity duration. Excavation in frozen ground is done at a different rate than under normal conditions. Plumbing tests cannot be conducted during the winter period in case of setting in of hard freeze. The uncertainty in weather conditions causes major delays for certain activities.

Space Congestion.—It may result from the physical features of the project or from high density of tradesmen working in one area. As the project progresses, different activities are advanced or delayed to meet the schedule changes. Consequently, activities under progress in a confined area may interfere with each other for working space requirement. Parviz shows in his study (10) that the overall estimate of lost time as a result of overcrowding was around five man hours/craftsmen/week. Productivity loss due to congestion, not being part of estimating activity duration, is generally not accounted for in schedule computations.

Crew Absenteeism.—Crew absenteeism can be a major menace on some projects. Its impact is well pronounced during winter when absenteeism is expected to be erratic and high. There seems to be considerable difference in absenteeism rate during week-ending and week-beginning days compared to mid-week days. Depending on crew formation, absenteeism of crucial tradesmen may even make it necessary to stop work on an activity.

Design Changes and Rework.—These are inevitable on any project and become unavoidable on projects when the design, construction, and commissioning phases overlap. Factors such as errors and omissions in the original design, incorporation of latest improvements, continuous change in safety and legal requirements, etc., necessitate changes resulting in extended duration for certain activities. As experienced on several projects, change orders are deleterious to the project schedule. The likelihood of changes is enhanced as additional agencies join the project team and their impact becomes more pronounced when the project is well advanced. Borcherding reports (4) that the cumulative time spent by each technician on rework activities amounts to 6 hrs/week.

Regulatory Requirements.—The Task Force to study the causes of the two years delay in Trans-Canada Pipelines lays the blame for the delay primarily on the time-consuming and often repetitive environmental assessment review process. Many projects must proceed under the continued threat of shutdowns, delays, harassment, and court challenges due to regulatory requirements. It is recognized that there will be more and more government regulations on: (1) Safety of the design and field construction methods; and (2) environmental consequences of project. These are expected to have significant impact on activity durations.

Economic Activity Level.—There is a relation between the number of ongoing projects and labor productivity based on the ratio of demand to the available skilled labor. As the number of projects increases, there is bound to be more demand for labor. If the labor is in short supply, it may result in recruitment of marginally qualified crew thereby reducing the overall productivity (8). In addition, the "turnover" increases dramatically affecting productivity.

Labor Unrest.—Labor unrest has many reasons; symptomatic among them are current contract expiry, wildcat strikes due to accident, management attitude, overtime problems, disciplinary action, etc. An environment of labor unrest bodes downturn in productivity varying with the type of activity, unions, etc.

Specific Uncertainty Variable

In addition, there may be a specific uncertainty variable that causes significant impact on the duration estimate of a particular activity. For example, drilling equipment failure may be a significant uncertainty variable for "Drill Well" activity. Such impacts are also to be considered.

To simulate the project environment and determine the impact of the uncertainty variables on the activity durations, it will be necessary to use historical data. Past behavior can give a basis for predicting future behavior. Determining the probability of future events requires the in-

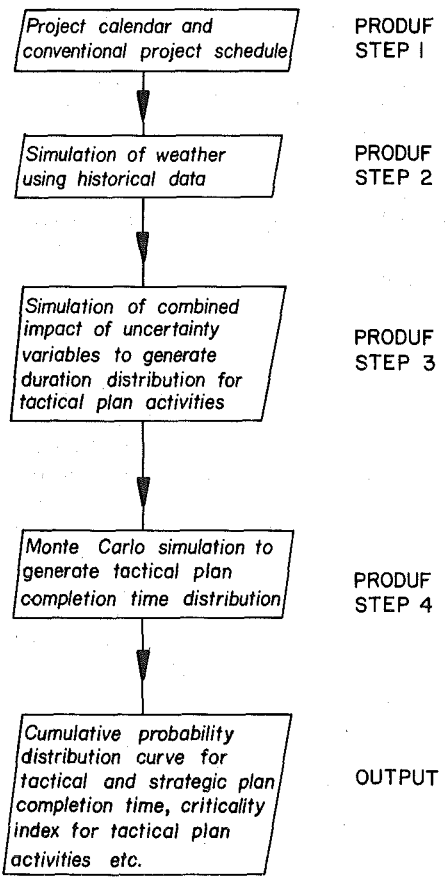

FIG. 3.—PRODUF Computer Model

fusion of additional intelligence or judgment, which implies the existence of a logic for relating variables to outcomes.

Computer Model

A computer model, Project Duration Forecast (PRODUF), has been formulated and is shown in Fig. 3.

PRODUF requires as input the following: (1) A strategic and a tactical plan; and (2) historical data on the significant uncertainty variables.

An example project will explain its working. It is proposed to consider a project for constructing a plant office-cum-warehouse (9). The schedule start date is 1st May 1984 and a monthly progress review and update is required.

Strategic and Tactical Plans

Fig. 4 shows part of the strategic plan comprising the major activities of the project and a tactical plan for three reporting periods. As the project proceeds, tactical plan is progressively extended one period at the time of each progress review so it always represents the current as well as the two following periods.

Generation of Project Calendar and Project Schedule.—Based on the start date of 1st May 1984 and user specified holiday list, the project calendar as well as the strategic and tactical schedules are generated. These schedules do not incorporate the impact of uncertainty variables.

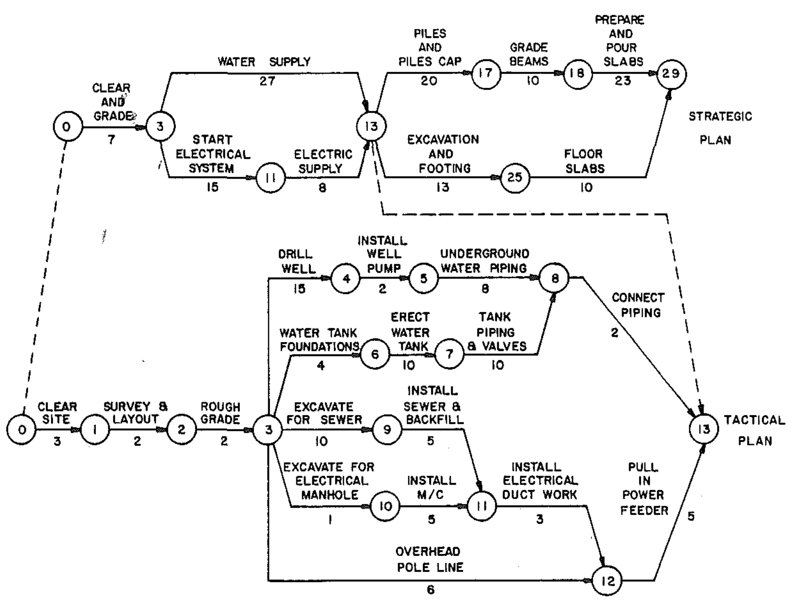

FIG. 4.—Strategic and Tactical Plans

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Collection of Historical Data on Uncertainty Variables

Since individual uncertainty variables have significant impact on specific activities, the data relating to the uncertainty variables and their likely range of impact are collected in a tabular form for each tactical plan activity and are systematically input interactively. The details of input required as well as of the simulation performed for each significant uncertainty variable follow.

Learning Curve: Input.—Activities that are likely to be affected are: volume of work, duration, time required to carry out unit volume of work, and variation expected in decremental constant for such activities.

1. Simulates the decremental constant and computes revised duration for the activity.

Weather: Input.—Activities likely to be affected are: 10 years weather data, such as maximum temperature, rain, snow, and workday loss expected for relevant activities (5) under different weather conditions, such as temperature <0° F, rain >15 mm, etc.

1. Simulates weather for each project day and calculates the expected work day loss due to weather for activities planned on that day. The workday loss can be a whole day or a part thereof.

Space Congestion: Input.—Activities likely to be affected are: details of congested zones and total space available in such zones, and space requirement for activities to be executed in these zones.

1. Simulates space requirement of activities planned on each day to determine any possible space congestion. In case of congestion, delays the activities that have float. If the affected activities are critical, computes the workday loss due to decreased productivity.

Crew Absenteeism: Input.—Activities likely to be affected are range of monthly percentage absenteeism separately for midweek days, weekend and week beginning days. Total manpower for each month of the tactical plan period and range of workday loss expected if one/two workmen are absent.

1. Simulates the number of absentees, if any, on a workday using the percentage absenteeism and total manpower. Considers the activities planned on each day and distributes randomly the absentees over the activities. Calculates the workday loss for the number of absentees.

Regulatory Requirement, Design Changes, and Rework: Input.—Activities likely to be affected are: range of expected daily workday loss or range of total workday loss expected at "end of activity."

1. Simulates the expected daily or "end of activity" workday loss using historical data.

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Economic Activity Level: Input.—Monthly expected value of the ratio of workmen required to their availability, and the equation for the relation between the productivity adjustment factor and this ratio.

1. Computes for each tactical plan month the productivity adjustment factor and multiplies it by the available workday.

Labor Unrest: Input.—Project days expected to have labor unrest, activities likely to be affected and expected workday loss.

1. Computes workday loss, if any for the activities planned to be performed on the days of labor unrest.

Specific Uncertainty Variable: Input.—Activities likely to be affected by a specific uncertainty variable, and expected range of delay at the end of the activity caused by the variable.

1. Simulates for the activity the number of days of delay.

PRODUF first simulates the impact of those uncertainty variables that are independent of time of the year and then simulates for each day the impact of the time-dependency uncertainty variables.

Working of the Model

PRODUF is first used prior to the project start. It starts with project day 1 and uses early start sort to separate activities planned for day 1. It simulates and calculates for each activity planned on that day, the workday loss expected because of uncertainty variables. However, since in real life, these uncertainty variables have a combined impact it is necessary to investigate which variables are mutually exclusive. When the impact of uncertainty variables is mutually exclusive, the expected workday loss is subtracted from the available workday. When it is not so, the collective workday loss is computed by employing correction for overlap (13) as suggested by John C. Wollery. The program combines the impact and determines from simulation whether whole or part of the workday is available for the activity. This is done sequentially for all activities planned for day 1. At the end of the day, PRODUF, by subtracting the available workday from the duration of the activities, calculates the remaining duration required to complete each activity in progress. The model proceeds to project day 2, 3, 4, and so on, one day at a time, until the estimated duration of an activity in progress is finished while the activity is incomplete. At this stage, the early start and finish dates of all incomplete activities are recalculated taking into account the remaining duration. While determining the remaining duration for the activities in progress, if it is zero, the activity is considered complete, and the elapsed time on that activity is taken as its expected duration under simulated project environment. For the activity expected to have a delay at its end, PRODUF combines such delays, corrects for the overlap, and determines the activity duration. Situations where the remaining duration is in terms of fractions of a day have been treated

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appropriately. When all the tactical plan project days have been simulated, the tactical plan activities are in one of the following categories: (1) Complete; (2) still in progress and incomplete; and (3) yet to start.

To obtain expected duration for an activity in progress, the remaining duration required to complete it is added to the time elapsed. Also, since it is impractical to predict quantitatively with confidence the impact of the uncertainty variables for a span longer than three reporting periods, the duration estimate of those activities that are yet to start beyond the three reporting periods are not revised. These computations give a set of expected duration for each tactical plan activity in the simulated environment.

To adequately represent the project environment, the number of simulations are determined from the statistical analysis of the project. Under each simulation of the expected project environment, the corresponding expected duration for each tactical plan activity is computed and a distribution of the expected duration is obtained. The duration distribution is similar to PERT with the following exceptions:

1. A distribution for duration estimate is available instead of three time estimates.
2. The distribution is generated by simulation while PERT activity duration estimates are generally intuitive.

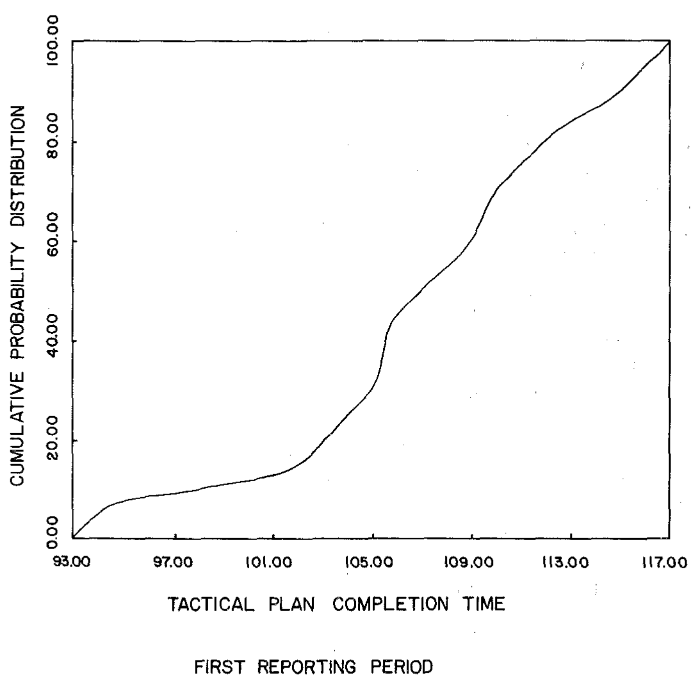

FIG. 5.—Cumulative Probability Distribution for Tactical Plan Completion Time

Using Monte-Carlo Simulation, a random duration estimate for each tactical plan activity is generated, forward and backward pass computations give the expected completion time. A distribution of the expected completion time is obtained through several iterations of the simulation process. Fig. 5 shows a cumulative distribution of the expected tactical plan completion time forecasted at the beginning of the first reporting period for the example project.

As the project proceeds, updating is required at specified intervals. Simulation during project updating requires the following additional input: (1) Start and end project day number for the tactical plan period under review; (2) activities completed; (3) activities in progress and their remaining duration; (4) modifications, if any, of the original plan activities; and (5) modification, if any, to the input data relating to the uncertainty variables.

PRODUF suitably modifies the existing data for use in computations of the probabilistic completion time for the tactical plan in subsequent progress reporting periods.

Flexibility of PRODUF Operation

PRODUF has been written in BASICA for use in microcomputers. Unlike package programs, the user can suitably modify it to suit his requirements. Bypassing of the impact considerations is possible to obtain deterministic reports for the field staff.

Special Features of PRODUF

1. PRODUF does not interrupt the existing procedures for collecting progress data, processing it and providing the field staff with updated action reports. It utilizes the historical and predicted data relating to the uncertainty variables to effectively forecast expected project delay or advancement during its tactical plan period. In case of an expected delay, the forecast alerts the management on the need for taking corrective action before problems arise.
2. The model replaces intuitive reviews of duration estimates by simulated duration distribution thereby permitting even the less experienced personnel to forecast project duration with a degree of accuracy and thoroughness.
3. It makes the management aware of the need to revise the original schedule when the project can no longer be brought back to its original schedule.

PRODUF has several possible applications, some of which are described in the following sections.

Forecasting Probabilistic Project Completion Time.—PRODUF can be used to forecast probabilistic project completion time. Graphs of such forecast made at the beginning of first and third reporting periods are shown in Figs. 6 and 7, respectively. These graphs show the probability trend of achieving the original schedule.

Figs. 6(*a*) and 7(*a*) represent the timeframe for the original tactical and strategic plans. There is a contingency provision at the end of the stra-

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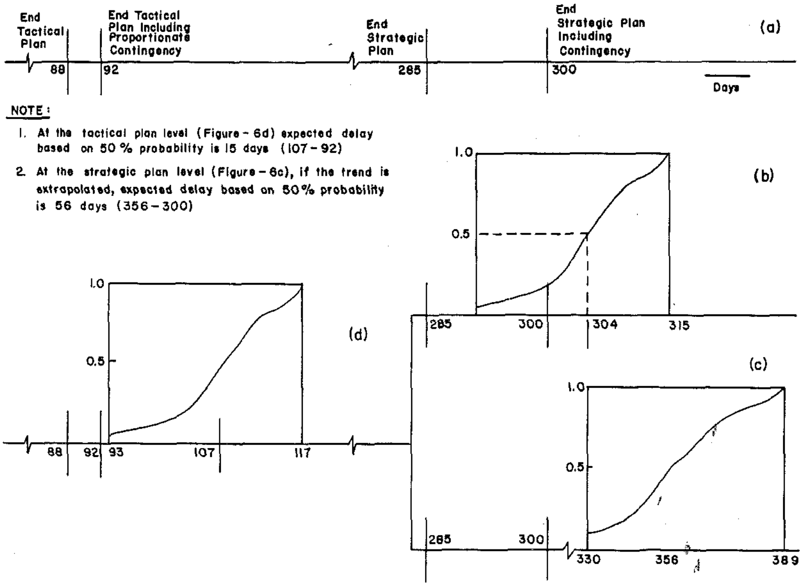

FIG. 6.—Probability Trend for Completion Time Just before Project Start

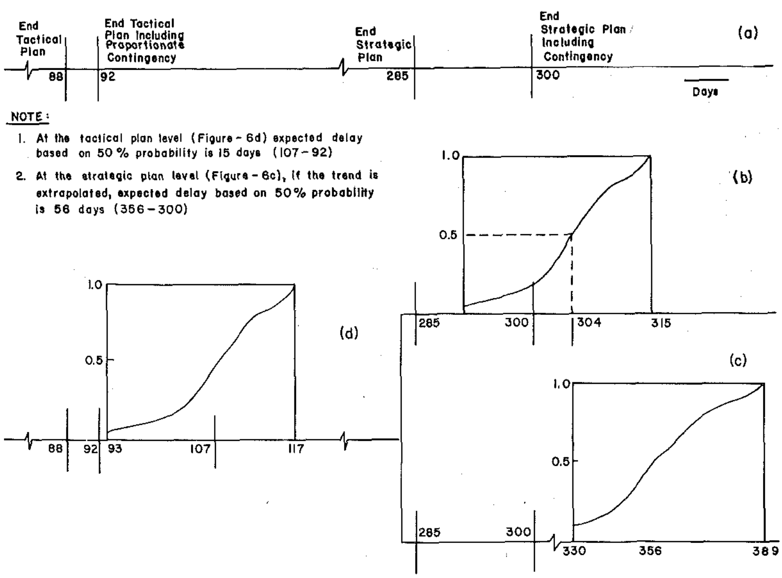

FIG. 7.—Probability Trend for Completion Time at End of Second Reporting Period

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tegic plan as well as a proportionate share thereof for the tactical plan.

Fig. 6(*d*) shows that there is 50% probability to complete the tactical plan in 107 workdays. The expected delay over the tactical plan period is 15 days (107 − 92). Fig. 7(*d*), for the third reporting period, shows no expected delay in the tactical plans indicating that the management has been successful in bringing the project back on its original schedule, thus requiring no schedule revision. Had the expected delay increased after the first reporting period, it would have indicated that the schedule was getting out of hand thus pointing out the need for schedule revision.

Figs. 6(*c*) and 7(*c*) show the probability trend of the project completion time based on extrapolations for the first and the third reporting periods, respectively. Fig. 6(*c*) shows a delay of 56 days, extrapolated for the strategic plan period. However, Fig. 7(*c*), for the third reporting period, shows no delay in expected completion of the project.

While generating the probability trend graphs for the project completion time, PRODUF also generates information on individual activities, which provides management with additional insight into the project. Based on the expected duration distribution of each activity, the management can focus its attention on the activities that have greater likelihood of deviating from the original duration. Management can take time cost tradeoff decisions to offset the delay.

Determination of Criticality Index.—The criticality index of an activity, very important for management by exception, can be defined as the ratio of the number of times an activity becomes critical out of total number of times the project duration is simulated. PRODUF generates a reliable criticality index incorporating the combined impact of the uncertainty variables.

Sensitivity of an Activity to Uncertainty Variables.—It is known that the uncertainty variables do not affect each activity alike. Some activities are more sensitive to certain variables than others. PRODUF forewarns the management by identifying the significant uncertainty variable that is expected to cause most delay in an activity.

Determination of Contingency Time Allowance.—PRODUF can be used to make realistic estimate of contingency time allowance for the project. By a suitable extrapolation from the forecast of expected delay for the first tactical plan period, the contingency time allowance can be estimated.

Gaming Model.—Construction management games like "CONSTRUCTO," "PERTSIM," and "PAMSIM" have been developed to give the student confined to the academic setting, the opportunity to develop the skeleton of his own response by confronting him with problems in the game environment similar to those actually encountered on job site.

PRODUF, with minor modifications, can also be used as a gaming model for demonstration to students. The following will be its main features:

1. Use of microcomputers instead of main frame computers used by the existing models.
2. Incorporation of the combined impact of a large number of uncertainty variables.

3. Extensive use of historical data on uncertainty variables for a specific project.
4. More realistic probabilistic forecast of project delay to enhance student's understanding of the impact of uncertainty variables.

As gaming model, PRODUF can also be used for personnel selection.

Use of PRODUF Model on a Hydro Project

PRODUF Model has been effectively used on a hydro project. The project was under construction and the dam at east and west were simultaneously in progress when the program was used. The project had a diversion tunnel to drain the runoff from the river that flowed into the reservoir. The gate to the diversion tunnel was to be closed permanently when the reservoir was ready to store water. The management would like to commission the project in November/December 1984 as soon as the construction was over. To maximize water storage in the reservoir for generating electricity, the diversion gate must be closed as early as possible so that enough of 1984 Spring runoff could be stored. Since the two dams were expected to be constructed during the Spring and must not be overtopped, a suitable date for gate closure has to be selected which would satisfy both constraints. From the weather data available for 15 years, the model simulated weather for each project day under consideration. Using observed weather productivity relationships, and workday type (holiday, half workday, full workday, or double shift) daily progress of dam construction was estimated. As a starting

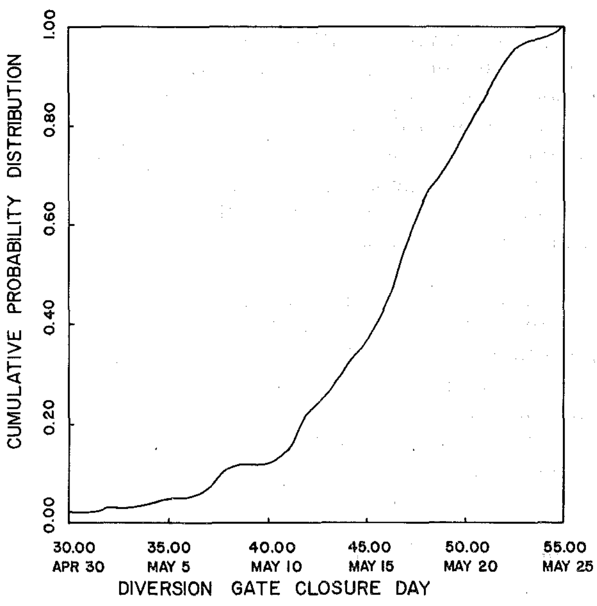

FIG. 8.—Cumulative Probability Distribution for Diversion Gate Closure

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point, the program considered a given date for diversion gate closure and generated an optimum date in such a way that the water level in the reservoir was always maintained at least one meter below the dam level to avoid overtopping of the dam. In the meantime, during construction of the dam, the Spring runoff was being stored. By simulation, a distribution of gate closure dates was plotted as shown in Fig. 8. The management selected the gate closure date commensurate with the risk it wanted to take. In addition, the program generated cumulative distribution curve for the likely start dates of dam construction. Also, depending on different gate closure dates and simulated runoff, distribution of the corresponding dates when the lowest supply level required to generate electricity would be reached, was determined. A cumulative distribution for the aforementioned date was also generated. Thus, PRODUF provided the management with valuable information to plan its construction and commissioning programs.

At this stage, it is relevant to examine the limitations of the model.

Limitations of the Model

1. The impact of the various significant uncertainty variables are considered only for three reporting periods represented by the tactical plan. However, the limitation helps keep the model within the realm of realism because it is impractical to predict with an appreciable degree of confidence the impact of the uncertainty variables for a period longer than three reporting periods.
2. The model has its foundation in the historical data available on uncertainty variables and its impact to refine the activity duration estimates and as such, the reliability of the output will be in direct proportion to the accuracy of the input data.
3. No statistical analysis has been made to quantify impact of the uncertainty variables. However, the use of such refined data will further enhance the reliability of the forecasts generated by PRODUF.

Conclusion

This paper has explained the various significant uncertainty variables that affect the duration of an activity while it is in progress. This, in turn, affects the project completion time. PRODUF simulates and combines the impact of the significant uncertainty variables and incorporates it in the activity duration estimates as it revises them. PRODUF uses Monte-Carlo simulation to forecast the expected delay in the tactical plan and strategic plan durations. It generates the criticality index for the tactical plan activities. The distribution of simulated project completion time is used to evaluate probability of completing the project by any scheduled date. Thus, the model fulfills its objective to comprehensively simulate the dynamic uncertainty variables and to incorporate their combined impact in activity duration estimates so that more reliable project completion forecasts become possible at each progress review. PRODUF is a major addition to the repertoire of existing project scheduling tools available in microcomputers.

Appendix.—References

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