Probabilistic Forecasting of Project Performance Using Stochastic S Curves

Gabriel A. Barraza, M.ASCE[1]; W. Edward Back, A.M.ASCE[2]; and Fernando Mata[3]

Abstract: This study presents a new methodology for evaluating at-completion project performance status. This new procedure uses the concept of stochastic S curves (SS curves) to determine forecasted project estimates as an alternative to using deterministic S curves and traditional forecasting methods. A simulation approach is used for generating the stochastic S curves, and it is based on the defined variability in duration and cost of the individual activities within the process. Stochastic S curves provide probability distributions for the budget and time values required to complete the project at every selected point of intermediate completion. Final project performance is determined by comparing the planned budget and project duration, with the expected forecasted final cost and elapsed time, respectively. The SS-curve methodology permits objective evaluation of project performance without the limitations inherent in a deterministic approach. The probabilistic characteristics of this approach enable users to more accurately determine at-completion cost and duration variations and evaluate the performance improvement of proposed corrective actions.

DOI: 10.1061/(ASCE)0733-9364(2004)130:1(25)

CE Database subject headings: Project management; Scheduling; Monte Carlo method; Simulation; Cost control; Forecasting; Performance evaluation.

Introduction

In the planning stage of a construction project, definition of the specific project activities and organization of the associated base schedule (time estimating), as well as development of an acceptable base cost estimate (cost estimating) must be undertaken. Both, the base cost estimate and the base schedule, include all items that are defined as most likely to happen.

When controlling project performance, it is important to not only monitor cost and time variances for actual project progress, but also to properly establish the actual project status based on objective predictions (forecasts) of final project performance. At-completion project performance can be predicted by comparing estimates of planned total budget and final duration with their respective most likely forecasted values (Ahuja et al. 1994). Such forecasts are necessary for the project manager to determine if corrective actions are required to minimize the expected variances from planned performance.

Accurate cost and schedule project forecasts are difficult to generate when considering the impact of such events as unforeseen cost changes, material delays, scope deviation, changes to the project execution plan, and poor subcontractor performance. In reality, the original estimate may be considered the first project forecast and, at the point of project completion, the latest updated estimate (last forecast) and the actual amount of what is being expended should be the same (Ward and Lithfield 1980).

Estimating both final cost and duration values can be performed using two different approaches: deterministic and probabilistic. The deterministic approach estimates final cost and project duration considering for the project activities the most likely cost and duration values, respectively. The probabilistic approach estimates the planned cost and duration values based on the variability of cost and duration inherent in each of the project activities. In spite of the improved representation of the variable behavior of projects that allows the probabilistic approach (Crandall and Woolery 1982), deterministic methods are more commonly used because they are based on simpler models.

The research described in this paper has the objective of developing a methodology for using a probabilistic model to determine at-completion project performance. Advantages of the method presented herein and recommendations for a simplified treatment of correlation between past performance and future performance are discussed in this paper. An application of this methodology to an example project is also presented.

Integrated Project Performance Forecasting

Integrated project performance includes the four main elements of a construction project: cost, schedule, quality, and safety (Oberlander 1993). In this research, integrated project performance should be understood as a comparison of the actual (real) project cost and schedule, with the planned budget and schedule.

An important aspect in performance forecasting of construction projects is the correct treatment of correlated variables. Deterministic methods treat performance correlation by setting equivalent the performance of future activities to the performance of past activities, or alternatively, adjusting future performance by

[1]Professor, Graduate School of Business Administration, Tec de Monterrey, Monterrey NL 64849, Mexico.

[2]Assistant Professor, Dept. of Civil Engineering, Clemson Univ., Clemson, SC 29630.

[3]Professor, Graduate School of Business Administration, Tec de Monterrey, Monterrey NL 64849, Mexico.

Note. Discussion open until July 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on September 21, 2000; approved on July 1, 2002. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 130, No. 1, February 1, 2004. ©ASCE, ISSN 0733-9364/2004/1-25–32/$18.00.

J. Constr. Eng. Manage., 2004, 130(1): 25-32

adopting a trend technique established from observations of past project performance. To effectively employ the latter technique, it is necessary to measure progress for several periods.

Most of the work completed to date with deterministic forecasting methods use performance trend analysis. Teicholz (1993) adopts a sliding moving average approach in his forecasting method that was found to be superior in accuracy, timing, and stability than assuming linear forecast of to-date project performance. Wheelwright (1995) evaluated various types of mathematical trend and subjective methods, and concluded that there is no (deterministic) forecasting technique that is superior in all situations and circumstances. However, Wheelwright states that simple techniques, such as moving average and simple exponential smoothing, might produce better results compared to complicated techniques. Dawood and Molson (1997) developed specifications for a strategy that predicts construction costs through integration of cost indices, forecasts, and construction plans. They implemented a system that uses a forecasting method that decomposes the time series data into three separate components: the trend, cyclical, and seasonal factors. They concluded that the decomposition technique produced better results than other forecasting techniques including simple moving average, single exponential smoothing, and exponential smoothing.

The more commonly used deterministic forecasting methods are based in the use of the earned value system (EVS). In the EVS, two different simple methods are recommended for evaluation of the estimated cost at completion (EAC). The first method, wish assumes independence between past cost performance and future cost performance, predicts EAC by adding the negative value of the actual cost variance (CV) to the budgeted cost at completion (BAC). The second method, considering correlation between future and past cost performance, predicts EAC by diving the BAC between the cost performance index (CPI). Once the EAC is determined, at-completion variance (ACV) is evaluated as the difference between BAC and EAC. The cost project performance is acceptable in any case that ACV is found with positive value [U.S. Department of Energy (U.S. DOE) 1979]. Although the EVS is considered as an integrated control approach, it does not provide an index to predict the final schedule performance since, because of its definition, schedule variance always equals cero when the project is at completion.

Recognizing the imprecision of deterministic forecasting methods, Neil (1987) recommends that no single (deterministic) forecasting method should be used, rather different (deterministic) methods should be included in a forecast providing a range of possibilities. Also, Ward and Lithfield (1980) state that it is important to recognize that project progress is continually subject to change, and hence a straight-line assumption is incorrect. Further, the employment of a forecast, predicated purely on previous performance, constitutes an incomplete forecasting technique. Therefore, to generate a realistic forecast, it is important to consider the strategy for the performance of the work for subsequent progress periods.

Most actual probabilistic forecasting methods treat performance correlation by using correlation coefficients during the forecast calculation (Fishman 1978; Rao and Grobler 1995). Probabilistic treatment of performance correlation in the project activities, using correlation coefficients in the simulation process, seems to be an objective but complex technique since it implies previous estimation of the correlation coefficients. Considering that, in most cases, such estimation is developed using subjective criteria, the performance correlation treatment loses overall objectiveness (Touran 1993).

In the opinion of Neil (1987), few constructors are comfortable with sophisticated forecasting techniques but, if contractors wish to improve the quality of estimates, they must utilize methods that are consistent with their probabilistic nature (Vergara and Boyer 1974). Today, for planning purposes, the simulation technique is commonly accepted for cost and duration estimating. Therefore, this technique could have more potential if it were used for project control purposes developing a more realistic evaluation of at-completion project performance by considering performance variability of future activities and a simplified treatment of the correlation factor.

Probabilistic Forecasting of Project Performance Using Stochastic S Curves

The probabilistic forecasting method proposed in this paper uses progress-based S curves (PB-S curves) as graphical representation and a simulation approach, for both developing integrated project monitoring and forecasting at-completion project performance.

This section presents the concepts of the methodology of probabilistic performance forecasting and describes the simulation computer program that was developed with the purpose of implementing an application of this methodology.

Progress-Based S Curves and Stochastic S Curves

Progress-based S curves are defined as plots of cumulative budget and planned duration against project progress (Barraza et al. 2000). Performance monitoring using PB-S curves is equivalent to the use of the EVS, however it has the advantage of representing the three units required to follow integrated performance: cost, time, and work (progress). Different criteria can be followed to evaluate the percentage of work performed (project progress) required for obtaining the PB-S curves. If the contribution of an activity to the progress of the entire project is evaluated as the percentage that the activity planned cost contributes to the total project budget, the plot of time versus progress resembles the shape of an inverted S and the plot of cost versus progress corresponds to a straight line.

The use of PB-S curves is a technique that allows the graphical representation of an integrated probabilistic performance forecast. Using a simulation approach and the PB-S curves representation, different possible total cost and project durations may be evaluated. Thus, for each simulation iteration, a possible PB-S curve can be plotted. Barraza (1998) defined the resulting set of PB-S curves as stochastic S curves (SS curves). By analyzing all possible values of cost and duration, probability distributions can be obtained for cost and duration at any specific percentage of work completed (progress). Fig. 1 shows SS curves and distributions of budgeted cost and project duration at each 10% increment of project progress. Distributions of possible values of at-completion budgeted cost (BAC) and at-completion schedule duration (DAC) can be analyzed at 100% of project progress.

Probabilistic Project Performance Monitoring and Forecasting

Monitoring of actual cost and schedule performances can be developed by evaluating actual cost and time variations (Barraza et al. 2000). Using a probabilistic approach, the CV is evaluated as the difference between expected budgeted cost for work performed (μ_{BCWP}) and actual cost for work performed (ACWP).

J. Constr. Eng. Manage., 2004, 130(1): 25-32

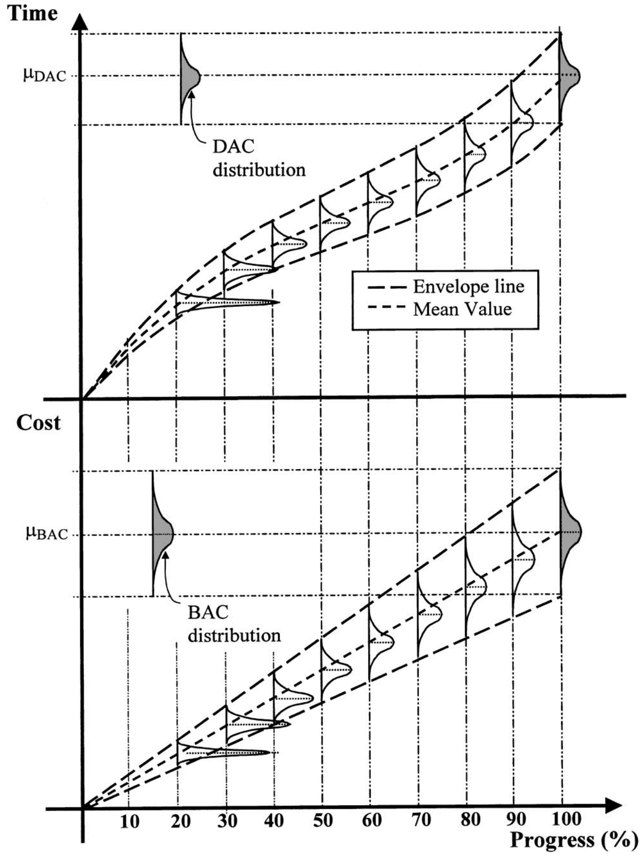

Fig. 1. Stochastic S curves applying progress-based S curves representation

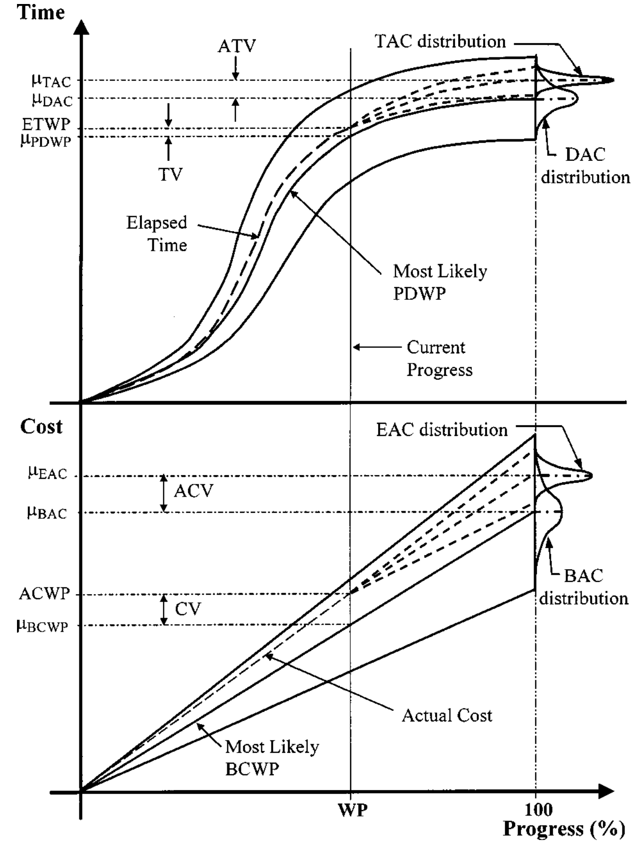

Fig. 2. Probabilistic performance forecasting using stochastic S curves

Similarly, time variation (TV) is evaluated as the difference between expected planned duration for work performed (μ_{PDWP}) and elapsed time for work performed (ETWP). Here the term ''variance,'' used in deterministic approaches, has been changed to the term ''variation'' because of the statistical meaning of the former term. Fig. 2 illustrates the CV and TV using the SS curves concept. Expected budgeted cost and planned duration, required to accomplish a specific project progress, can be obtained from the respective budget and duration distributions.

Using the actual cost and duration data for all activities already completed and simulating the performance of future activities, predictions of cost and duration for future project progress can be created. If cost and duration are predicted (simulated) for total progress (100% of work completed), distributions of estimated cost (EAC) and elapsed time at completion (TAC) are obtained. At-completion cost variation is then evaluated as the difference between expected BAC (μ_{BAC}) and expected EAC (μ_{EAC}). In addition, at-completion time variation (ATV) is evaluated as the difference between expected DAC (μ_{DAC}) and the expected TAC (μ_{TAC}). Eqs. (1) and (2) are used to calculate ACV and ATC, and Fig. 2 illustrates their correspondent graphical representations.

$$ACV = \mu_{BAC} - \mu_{EAC} \tag{1}$$

$$ATC = \mu_{DAC} - \mu_{TAC} \tag{2}$$

Using this technique, positive at-completion variations represent acceptable forecasted project performance.

Treatment of Performance Correlation

As an alternative to the use of correlation coefficients in probabilistic forecasting, an equivalent technique to those used in deterministic methods can be implemented. This is accomplished by developing the probabilistic forecasts of EAC and TAC, as if the performance of future work and completed to-date work were independent after the individual performance for future activities had been adjusted using one of the two methods proposed in the EVS: Method 1, for future performance as originally planned and; Method 2, for future performance equal to past performance. Thus, probabilistic estimations of cost and schedule performance will consider both the correlation between past and future activity performance and, the predicted performance variability of future activities themselves.

Since probabilistic methods estimate activity performance using cost and duration probability distributions, performance correlations may be treated considering two cases: (1) when an activity is in process at the moment that performance monitoring is developed, final cost and duration for such activity can be estimated by applying Eqs. (3) and (4) (Method 1) if future performance is independent or Eqs. (5) and (6) (Method 2) if future performance is dependent of previous performance; (2) when future activities have not been started and correlation exists with already finished activities, parameters of probability distributions (i.e., mean and standard deviation values) of future activities can be adjusted with Eqs. (5) and (6), by directly using the CPI and the time performance index of already finished activities (Method 2). Once cost and duration parameters of the probability distribution are adjusted for in process and not started activities, probabilistic project forecasts may be developed in the usual manner

J. Constr. Eng. Manage., 2004, 130(1): 25-32

(as if activities were independent). Note that performance parameters used in Eqs. (3)–(6) are all at activity level

$$\mathrm{EAC} = (\mathrm{ACWP}) + (\mathrm{BAC\text{-}BCWP}) \tag{3}$$

$$\mathrm{TAC} = (\mathrm{ETWP}) + (\mathrm{DAC\text{-}PDWP}) \tag{4}$$

$$\mathrm{EAC} = \mathrm{BAC}\left(\frac{\mathrm{ACWP}}{\mathrm{BCWP}}\right) = \frac{\mathrm{BAC}}{\mathrm{CPI}} \tag{5}$$

$$\mathrm{TAC} = \mathrm{DAC}\left(\frac{\mathrm{ETWP}}{\mathrm{PDWP}}\right) = \frac{\mathrm{DAC}}{\mathrm{TPI}} \tag{6}$$

Stochastic Performance Control with Integrated Stochastic S Curves

Stochastic Performance Control with Integrated SS curves (*SPECIESS*), a simulation computer program, enables the user to administer a project making use of the theory of integrated stochastic S curves (SS curves) developed by Barraza (1998). Stochastic Performance Control with Integrated Stochastic S Curves works inside MS Excel through macros programmed in Visual Basic. Stochastic Performance Control with Integrated Stochastic S Curves has been programmed into modules that perform the calculations needed to develop probabilistic project management capability, providing information useful in the planning roles (i.e., scheduling and cost estimating) as well in the control roles (i.e., monitoring and forecasting).

Stochastic Performance Control with Integrated Stochastic S Curves operation is simple and friendly requiring the user to only fill in an Excel Workbook Template. The required information is organized into a table format including time, cost, percent of work, and precedence relationship data for each of the project activities as well as some of the user preferences. Among such preferences there are the number of iterations that *SPECIESS* is to perform and the percentage increment of project progress used in the SS curves computations. An expected (overall) indirect cost per working day can also be included in the project information. The results of the calculations performed by *SPECIESS* are conveniently organized and written in individual worksheets. The user is also able to make custom charts for the information generated by this program (i.e., SS curves).

Application

To demonstrate the functionality of the probabilistic forecasting technique, it was necessary to identify a project that, without being too complex, would allow experimentation with variations in the cost and duration of its activities in such a way that it would be possible to find diversity in critical paths and clear variability in the project performance distributions (SS curves).

The project used as an example is the construction of a prestressed concrete girder bridge of three 30 m spans, with a cast-in situ deck, supported on two river piers and two abutments on level banks (Antil and Woodhead 1990). The piers and abutments have precast concrete pile foundations, with pile caps below water level, each, therefore, requiring cofferdams. A girder casting yard was necessary on the site, and the prestressed girders could easily be transported by trolleys running on rails across the flat banks and over the river on falsework. The concrete piles were to be supplied by the owner 15 days after moving-in tasks had begun. A 40 h work week was originally considered for all activities except for pile driving and construction of the cofferdam for which a 45 h week was planned. Indirect cost and overhead were originally estimated at $360/working day.

Most likely values for direct cost and duration of the planned project activities are presented in Table 1. This table also shows the percentage of total work assigned to each activity (column 7), calculated as the ratio between the correspondent cost mean value and sum of all activity cost mean values. The project network is shown in Fig. 3 where activities 26 and 28 were grouped for simplicity of the drawing since they are concurrent and have the same predecessors and successors. Activities 27 and 29 are treated similarly though, they are considered independent activities for calculation purposes.

To somewhat simplify the variability estimation of direct costs and durations for the project activities, normal distributions were assumed for all activities. These distributions were defined with mean (expected) values equal to the most likely values given in Table 1 for both duration and direct cost; while standard deviations were estimated as a percentage of the correspondent expected values, 10% for activity durations and 5% for activity direct costs. For the purpose of this example, it is assumed that productivity rates, under normal conditions, are well known, and all variations result from weather, soil, and river conditions. Thus, all activities are considered noncorrelated since weather, soil, and river conditions can be different for each activity.

Running 500 project simulations in *SPECIESS*, the expected estimations of project duration and final cost were obtained from the simulated SS curve values and from the correspondent cumulative distribution functions at project completion (100% of work complete). Such values were 289 days of project duration, $104,020 of indirect cost, $632,669 of direct cost, and $736,688 of total costs. Figs. 4 and 5 show time and direct cost SS curves, respectively.

To illustrate the methodology for project monitoring at intermediate points of project completion, the project was first examined at Day 50. The assumed actual activity costs, and the start and finish dates shown in Table 2, were updated in *SPECIESS*. At Day 50, activities 1 and 2 were finished, and activities 3, 12, and 22 had achieved partial completion. Overall actual indirect costs were estimated with average value of $355/day. Project work completion was calculated by *SPECIESS* as 10.4%. The reported time and cost performance is summarized in Table 3 where actual elapsed time and actual costs (ETWP and ACWP, respectively) are presented. This table also shows values of the expected planned duration and budgeted costs for actual work performed (μ_{PDWP} and μ_{BCWP}, respectively). In this table, actual positive (or almost zero) variations show overall acceptable performance. Thus, no further analysis was required and the project was permitted to proceed in accordance with the original plan for execution.

For the next monitoring event, 100 working days had elapsed and project progress was assumed as follows: Activities 1, 2, 3, 5, 7, 12, 13, and 16 were completed, and activities 8, 14, and 22 are in execution. Table 4 provides more detailed information regarding activity performance. Overall indirect costs were estimated with the average value of $355/day (as in the previous monitoring period). Stochastic Performance Control with Integrated Stochastic S Curves found that project work completion is at 32.6% and the evaluation of time and costs performances is as shown in Table 5. Graphical representations of schedule and total cost monitoring, also obtained with *SPECIESS*, are shown in Figs. 6 and 7, respectively. Table 5 indicates negative time slippage (-2 days) and total cost overrun ($\$-1{,}939$). Thus, it was required to forecast final project performance based on at-

J. Constr. Eng. Manage., 2004, 130(1): 25-32

Table 1. Three Span Bridge—Project Activity Data

Act.	Arc	Description	Durat. (days)	Cost ($)	Work (%)
1	Λ-B	Mobilization	30	9,000	1.4
2	Λ-C	Girder casting yard	30	12,600	2.0
3	B-D	Drive piles in Abutment A	24	7,800	1.3
4	N-R	Drive piles in Abutment B	24	8,100	1.3
5	F-H	Drive piles in Pier no. 1	23	8,100	1.0
6	J-L	Drive piles in Pier no. 2	23	6,000	1.0
7	D-F	Cofferdam—install at Abutment A	15	16,000	2.9
8	H-J	Cofferdam remove—install Pier 1	20	21,000	3.3
9	L-N	Cofferdam remove—install Pier 2	20	21,000	3.3
10	R-U	Cofferdam remove—install Abut. B	20	21,000	3.3
11	V-W	Cofferdam remove from Abut. B	15	3,000	0.5
12	B-E	Erect falsework in Span 1	25	12,000	1.9
13	E-I	Erect falsework in Span 2	25	12,000	1.9
14	I-M	Erect falsework in Span 3	25	12,000	1.9
15	Y-Ω	Remove falsework, all spans	20	6,000	0.9
16	F-G	Reinforced concrete, Abutment A	20	15,000	2.4
17	J-K	Reinforced concrete, Pier 1 (1/2)	20	16,500	2.6
18	K-P	Reinforced concrete, Pier 1 (1/2)	20	16,500	2.6
19	N-Q	Reinforced concrete, Pier 2 (1/2)	20	16,500	2.6
20	Q-T	Reinforced concrete, Pier 2 (1/2)	20	16,500	2.6
21	U-V	Reinforced concrete, Abutment B	20	15,000	2.4
22	C-O	Manufacture PC Girders, Span 1	70	96,000	15.2
23	O-S	Manufacture PC Girders, Span 2	65	96,000	15.2
24	S-W	Manufacture PC Girders, Span 3	65	96,000	15.2
25	P-T	Erection of PC Girders, Span 1	15	5,400	0.9
26	T-W	Erection of PC Girders, Span 2	15	6,000	0.9
27	W-X	Erection of PC Girders, Span 3	15	6,600	1.0
28	T-W	In-situ concrete deck, Span 1	15	9,000	1.4
29	W-X	In-situ concrete deck, Span 2	15	9,000	1.4
30	X-Y	In-situ concrete deck, Span 3	15	9,000	1.4
31	X-Z	Approaches, handrails, etc.	30	21,000	3.3
32	Z-Ω	Clean up and move out	10	6,000	0.9

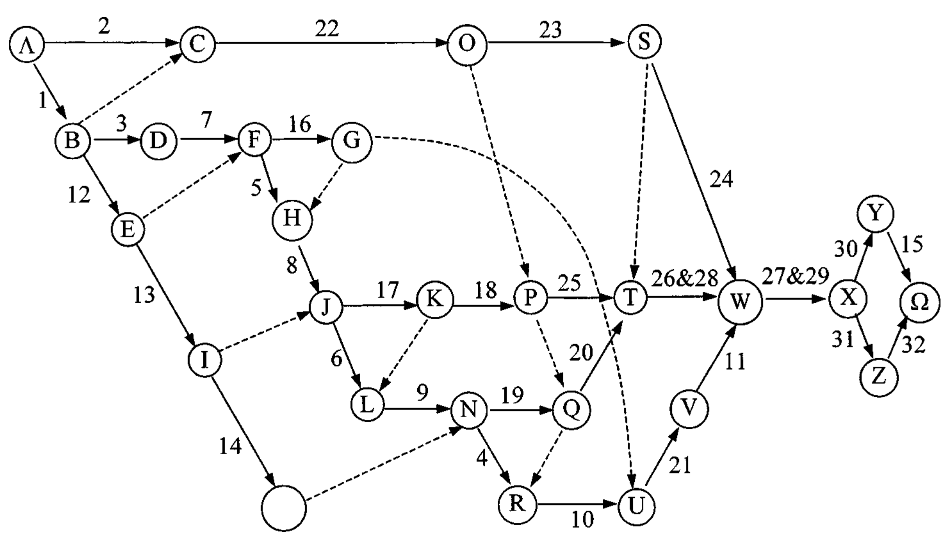

Fig. 3. Three span bridge—planned project network

J. Constr. Eng. Manage., 2004, 130(1): 25-32

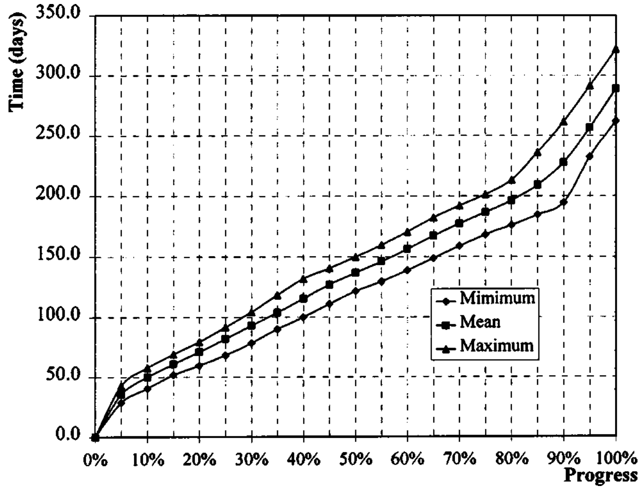

Fig. 4. Three span bridge—time stochastic S curves

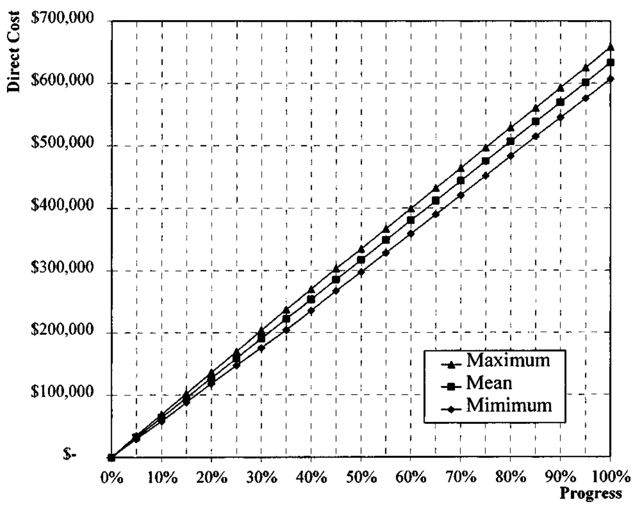

Fig. 5. Three span bridge—direct cost stochastic S curves

Table 2. Three Span Bridge—Actual Project Data at Day 50

Activity	Work completed	Start date	Finish or actual date	Direct cost
1	100%	0	28	$ 8,800
2	100%	0	30	$ 12,700
3	85%	28	50	$ 6,902
12	85%	28	50	$ 10,200
22	28%	30	50	$ 27,019

Table 3. Three Span Bridge—Project Performance Monitoring at Day 50

Concept	Expected	Actual	Variation
Time	50.6 days	50 days	0.6 days
Indirect cost	$ 18,221	$ 17,750	$ 471
Direct cost	$ 65,616	$ 65,621	$ (5)
Total cost	$ 83,837	$ 83,371	$ 466

Table 4. Three Span Bridge—Actual Project Data at Day 100

Activity	Work completed	Start date	Finish or actual date	Direct cost
1	100%	0	28	$ 8,800
2	100%	0	30	$ 12,700
3	100%	28	54	$ 8,120
5	100%	68	92	$ 6,500
7	100%	54	68	$ 18,150
8	40%	92	100	$ 8,650
12	100%	28	54	$ 10,416
13	100%	54	79	$ 12,400
14	83%	80	100	$ 10,500
16	100%	68	88	$ 15,200
22	97%	30	100	$ 93,600

completion cost and duration variations. Before running the *SPECIESS* program the remaining cost and duration of activities, already started but still in process, were estimated using Method 2 [Eqs. (5) and (6)] which assumes that their future performance is correlated with their past performance.

Table 6 shows *SPECIESS* output for at-completion project performance with respect to the forecasted project duration and final cost. From this table can be observed that at-completion time variation and total cost variation were found with negative values ($ATV = -3$ days and $ACV = \$-2{,}270$, respectively). If such negative values were considered as unacceptable, corrective actions should be proposed and evaluated.

Once the project data had been updated with the corrective action, a new project performance forecast could be run in order to evaluate effects in the probabilistic schedule and the revised at-completion performance forecast. If revised at-completion cost and duration variances were improved with respect to the originally forecasted values, the proposed corrective action could be considered as acceptable.

Summary and Discussion

A probabilistic forecasting method has been proposed in this paper for evaluation of at-completion project performance. This method presents the management advantages of: (1) consideration of an integrated performance analysis; (2) consideration of performance variability of future activities; and (3) consideration of correlation between past performance and future performance.

The probabilistic forecasting method, proposed herein, uses the progress-based representation of elapsed time and cumulative cost (PB-S curves). Using a simulation approach, a sample of stochastic PB-S curves (SS curves) can be obtained which provide cost and time distributions at any percent of work performed (project progress). Comparing planned SS curves and forecasted SS curves (including actual performance), estimations of at-

Table 5. Three Span Bridge—Project Performance Monitoring at Day 100

Concept	Expected	Actual	Variation
Time	98 days	100 days	−2 days
Indirect cost	$ 35,267	$ 35,500	$ (233)
Direct cost	$ 204,914	$ 206,620	$ (1,706)
Total cost	$ 240,181	$ 242,120	$ (1,939)

J. Constr. Eng. Manage., 2004, 130(1): 25-32

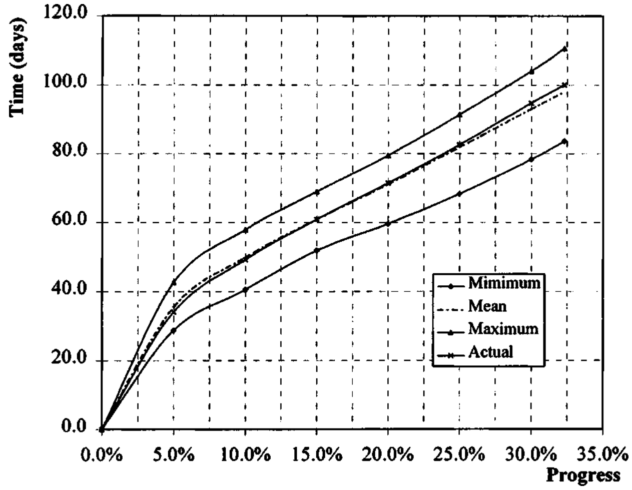

Fig. 6. Three span bridge—monitoring of elapsed time at day 100

completion performance variations are obtained to evaluate the final performance and determine the need for corrective action.

The use of the presented methodology can be implemented by analyzing the possible values of total cost and project duration for the originally planned estimates and for the forecasted estimates considering cost and elapsed time at actual project progress.

An application of the probabilistic forecasting methodology using the concept of stochastic S curves (SS curves) was presented and applied to an example project using *SPECIESS*, the simulation computer program developed for such purpose. In this application, the inherent variability in duration and cost of the project activities was considered not only in the cost and schedule base estimations, but also in the performance control of the proposed example.

Instead of using the probabilistic treatment of correlation coefficients, which in most cases are evaluated using a subjective estimation, the proposed probabilistic forecasting method uses methods similar to those recommended in the EVS methodology to account for performance correlations prior to performing simulations. These methods result in a simpler procedure than the probabilistic treatment of correlation coefficients and its accuracy can be as acceptable as the use of probabilistic correlation coefficients, considering these were subjectively evaluated.

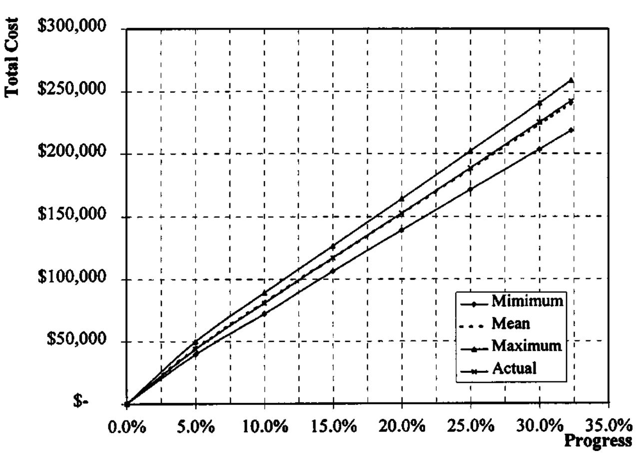

Fig. 7. Three span bridge—monitoring of total cost at day 100

Table 6. Three Span Bridge—Project Performance Forecasting at Day 100

Concept	Target	Forecast	Variation
Time	289 days	292 days	−3 days
Indirect cost	$ 104,020	$ 103,592	$ 428
Direct cost	$ 632,669	$ 635,367	$ (2,698)
Total cost	$ 736,688	$ 738,958	$ (2,270)

The project example, used as a representative application of the probabilistic forecasting method using SS curves, shows recommended criteria for evaluation of at-completion performance of construction projects. This methodology, with the advantages listed previously, may significantly improve the decision making process during construction execution. Therefore, the process of project control could be more meaningful if, besides the use of at-completion variances analysis, a probabilistic analysis of the project contingencies could also be considered.

Notation

The following symbols are used in this paper:

ACV = at-completion cost variation;
ACWP = actual cost for work performed;
BAC = at-completion budgeted cost for work scheduled;
BCWP = budgeted cost for work performed;
CPI = cost performance index;
DAC = at-completion scheduled duration;
EAC = at-completion forecasted cost;
ETWP = elapsed time for work performed;
PDWP = planned duration for work performed;
TAC = at-completion forecasted elapsed time;
TPI = time performance index; and
μ = expected value of probability distribution.

References

Ahuja, H. N., Dozzi, S. P., and AbouRizk, S. M. (1994). *Project management*, 2nd Ed., Wiley New York.

Antill, J. M., and Woodhead, R. W. (1990). *Critical path methods in construction practice*, 4th Ed., Wiley, New York.

Barraza, G. A. (1998). ''Probabilistic project control using integrated stochastic S Curves.'' PhD dissertation, Tecnólogico de Monterrey, Monterrey, NL, México.

Barraza, G. A., Back, W. E., and Mata, F. (2000). ''Probabilistic monitoring of project performance using SS-curves.'' *J. Constr. Eng. Manage.*, 126(2), 142–148.

Crandall, K. C., and Woolery, J. C. (1982). ''Schedule development under stochastic scheduling.'' *J. Constr. Div., Am. Soc. Civ. Eng.*, 108(2), 321–329.

Dawood, N., and Molson, A. (1997). ''An integrated approach to cost forecasting and construction planning for the construction industry.'' *Proc., Computing in Civil Engineering*, ASCE, Reston, Va., 535–542.

Fishman, G. S. (1978). *Principles of discrete simulation*, Wiley, New York.

Neil, J. (1987). ''Project control for construction. Construction industry institute.'' *Publication 6-5*, Univ. of Texas, Austin, Tex.

Oberlander, G. D. (1993). *Project management for engineering and construction*, McGraw-Hill, New York.

Rao, G., and Grobler, F. (1995). ''Integrated analyses of cost risk and schedule risk.'' *Proc., 2nd Congress in Computers in Civil Engineering*, ASCE, New York, 1404–1411.

J. Constr. Eng. Manage., 2004, 130(1): 25-32

Teicholz, P. (1993). ''Forecasting final cost and budget of construction projects.'' *J. Comput. Civ. Eng.*, 7(4), 511–529.
Touran, A. (1993). ''Probabilistic cost estimating with subjective correlations.'' *J. Constr. Eng. Manage.*, 119(1), 58–71.
U.S. Department of Energy (U.S. DOE). (1979). ''Cost and schedule control systems criteria for contract performance measurement.'' *DOE/CR-0014*, Washington, D.C.
Vergara, A., and Boyer, L. (1974). ''Probabilistic approach to estimating and cost control.'' *J. Constr. Div., Am. Soc. Civ. Eng.*, 100(4), 543–552.
Ward, S. A., and Lithfield, T. (1980). *Cost control in design and construction*, McGraw-Hill, New York.
Wheelwright, C. (1995). *Forecasting methods for management*, 4th Ed., Wiley, New York.

J. Constr. Eng. Manage., 2004, 130(1): 25-32