CONTINUOUS ASSESSMENT OF PROJECT PERFORMANCE

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ABSTRACT: Project managers for owners, designers, and contractors need real-time information to assist them in managing projects. This paper describes a process whereby owner, engineer, and construction contractor organizations can use continuous or time-dependent variables (e.g., owner expenditures, construction effort hours expended) to predict project outcomes from start of detailed design through construction completion. Continuous variable data were collected on 54 construction projects. S-curves were developed for two project outcome categories: (1) "successful" (meeting or exceeding budget and schedule expectations); and (2) "less-than-successful" (not meeting budget and/or schedule expectations of the owner). Statistical analysis was performed to identify those variables showing a statistically significant difference between the two project outcome categories. Variables exhibiting a significant difference between the S-curves for "successful" and "less-than-successful" projects can be used as predictors of project outcome. Results show that different variables were predictors of success at different points of time during the project life cycle. Practical applications of these results along with limitations and future research are described.

INTRODUCTION

Project managers are responsible for the overall success of a construction project, which includes meeting goals related to cost, schedule, quality, and safety. To help achieve these objectives, standard control techniques are used that typically involve a comparison of actual to estimates values; corrections are made if significant deviations exist. This approach assumes that if the actual values are close to the planned values, the project will achieve a successful outcome. The current approach has the following limitations: (1) the comparison is only as good as the estimated values for cost and schedule; (2) there is no certainty or prediction of achieving a successful outcome; and (3) normally only a few key variables are monitored.

The purpose of this paper is to describe a process where project managers can use continuous or time-dependent variables to predict project cost and schedule outcomes from the start of detailed design through construction completion. It is believed that relating these variables (e.g., owner expenditures and construction effort hours expended) to cost and schedule project outcomes can provide an enhanced control tool for project managers. To use a meteorological analogy, project managers want to know if there is a storm on the horizon. When forecasting the weather, meteorologists combine information gathered from many different sources (e.g., temperature, wind speed, barometric pressure, and satellite photographs). By monitoring the way this information changes over time, the meteorologist is able to predict the weather with some degree of accuracy. Project managers also have access to vast amounts of data that can be used to predict a project's outcome.

METHODOLOGY

The hypothesis of this research relates to the ability of using continuous or time-dependent variables to predict project cost and schedule outcomes. A continuous variable is defined as a time-dependent quantity whose value can be collected at several points during the course of a project (e.g., contractor expenditures, invoices paid by the contractor, owner project commitments, and designer cost) (Lawrence 1995). Variables that demonstrate a significant difference between the S-curves for two outcome categories are: (1) "successful"; and (2) "less-than-successful" projects that can be used as predictors of success. From an owner's perspective, a successful project is defined as one that meets or exceeds budgetary and schedule expectations while less-than-successful projects fail to meet budgetary and/or schedule expectations. The methodology for this research includes several steps: (1) identify continuous project variables; (2) develop a data collection tool and collect data; (3) analyze data; (4) determine results; and (5) show practical applications.

IDENTIFICATION OF CONTINUOUS PROJECT VARIABLES

Continuous project variables were identified with the assistance of the Construction Industry Institute Predictive Tools task force. Based upon the collective experience of task force members, variables were identified for both owners, designers, and contractors and selected because of their suitability for predicting a project's outcome as well as data availability. A total of 76 continuous variables were identified (see Appendix I). It should be pointed out that a continuous variable is measured in terms of money or effort hours. These measures, however, may be converted to a percentage (ratio of to-date to planned). In addition, these measures may take the form of committed, expended, invoiced, or payed. Some variables may be measured by the number of occurrences (i.e., frequency) such as facilities and days lost due to weather.

The variables used in examples found in this paper are defined next. For a definition of variables not used in this paper contact the first author.

Owner Expenditures

Owner expenditures is the amount of budgeted capital expended by the owner on the project. This includes design, procurement, and construction costs, as well as contingency, land, license fees, owner management staff, and interest on borrowed capital.

Contractor Construction Efforts Hours Expended

This is the number of craft effort hours expended during construction by all prime contractors and subcontractors in the form of field labor after budget appropriation.

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Invoices Paid by Contractor

This is the total dollar amount of invoices paid by the contractor organization (includes costs for material; equipment; labor; and overhead and profit paid to subcontractors and vendors).

Total Commitments for Material and Equipment

This is the total dollar amount of purchase orders written for all materials and installed equipment, including engineered equipment. (Contractor's commitments include both direct and indirect commitments, while owner commitments are direct commitments only. Therefore, owner's direct commitments plus contractor's commitments equals total commitments).

Cost of Owner Project Commitments and Cost of Contractor Project Commitments

This is the total dollar amount of contracts awarded by the owner and their contractor(s). This includes costs for material; equipment; labor; and overhead and profit paid to contractors, subcontractors, and vendors.

Designer Project Cost

This is the amount of money expended by the designer for actual engineering design. It includes all money expended by the designer to-date for actual engineering design. The cost provides the sum of all designers if multiple designers were used on the project.

DATA COLLECTION PROCESS

This process began by developing a 41-page data collection tool. The tool consisted of three parts: (1) definitions; (2) general information; and (3) continuous variables. This tool was pretested using three pilot projects. Revisions were made based on the input received from both the pilot project participants and task force.

This tool was mailed to the participating companies approximately two weeks prior to the scheduled interviews. Project participants were asked to assemble as much of the data as possible and fill in the appropriate pages. Next, the research team conducted a personal interview with each respondent to review the data and perform rudimentary verification.

A total of 54 completed projects (45 successful and nine less-than-successful) were provided by 17 Construction Industry Institute (CII) companies (Lawrence 1995). These organizations consisted of both public and private owners, as well as design and construction contractors. The comprehensiveness of completing the data collection tool varied from approximately 10 to 55% complete. A sufficient amount of data, however, was collected to demonstrate the concept of using continuous variables as predictors of project cost and schedule outcomes.

DATA ANALYSIS

To compare projects of different size and duration, the data were normalized on a percentage basis. For example, the x-axis represents time from 0 to 100% project complete; while the y-axis represents the normalized value of each continuous variable (e.g., owner commitments to-date divided by the planned owner commitments for the entire project). Furthermore, data on each of the variables studied were differentiated by a variety of project parameters. A parameter is a project-specific characteristic whose value does not change over the course of a project. Examples of project parameters include: construction type, organization type, project size, and designer and construction contract type. Data were analyzed considering: (1) no differentiation of parameter type (i.e., all project data); (2) differentiation by one parameter at a time (e.g., all projects using a lump sum construction contracting approach); and (3) differentiation by multiple parameters (e.g., all process projects using a lump sum construction contracting approach).

Due to the amount and complexity of the data collected, a computer program was developed to assist in the analysis process. The 2.0 version of this program, Continuous Assessment of Project Performance (CAPP), runs on Microsoft Windows platform (Russell and Jaselskis 1996). The software consists of four modules: (1) data input; (2) data normalization; (3) statistical analysis; and (4) graphical report generation.

CAPP provides a user-friendly icon-driven data input screen. This feature allows users to add new project data into the database. The data normalization module performs the normalization of this time variable in the horizontal axis and the selected variable in the vertical axis. The statistical analysis portion analyzes the significance of the difference between the two project outcome categories for each variable and identifies where (i.e., on the x-axis or time) it is a predictor of project outcome. Hypothesis tests were conducted using the student's t-distribution to determine the level of statistical significance. A significant difference existed when the value of alpha (type I error) was less than or equal to 0.10. The graphical module generates the S-curves for the successful and less-than-successful projects and the real-time project control charts. A real-time control chart consolidates all the variables that are statistically significant. Only the portions where the variable is showing significance is plotted on the chart. The software provides the flexibility to analyze data from different perspectives: (1) project type (e.g., process plant, manufacturing, general building, among others); (2) project size; (3) organization type (e.g., owner, contractor, or designer); and (4) contract strategy for designer and constructor (e.g., lump sum and reimbursable cost). A more complete description of the software program can be found in Russell et al. (1996).

RESULTS

Project Characteristics

The 54 projects were predominantly process projects (65%) (e.g., petrochemical, chemical, food, and paper projects) with others in manufacturing (e.g., steel, automotive, and consumer product production); power (e.g., coal, cogeneration, nuclear, and other projects related to power production); general building (e.g., office, institutional, and other commercial projects); environmental (e.g., landfill and environmental cleanup projects); and heavy civil. Projects varied in size from $2,000,000 to approximately $500,000,000 with an average project size of $77,000,000 and a standard deviation of $109,000,000. Project durations, from the beginning of detailed design to the completion of construction, ranged from seven to 81 months with an average duration of 26 months and a standard deviation of 16 months. The database contains three project delivery approaches: (1) engineer-procure-construct (69%); (2) design-bid-build (27%); and (3) construction management (4%).

The database also includes projects from both extremes: from 0% for an emergency project where construction began simultaneously with design, to 100% where the project's design was completed prior to the start of construction. Half of the projects began construction activities before design was 50% complete. Seventy-two percent of the designer contracts were reimbursable with 28% being lump sum. Fifty-four percent of the construction contract types were reimbursable while 46% were lump sum.

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Continuous Variables as Predictors of Project Outcome

Several continuous variables were found to be predictors of project outcome. It was discovered that a variable's predictive capability depended on the project parameters selected (e.g., lump sum versus reimbursable cost projects) and the project phase. It was interesting to note that some variables were better predictors of project outcome during early project stages while others were better predictors during later project phases.

Fig. 1 shows the CAPP generated S-curves for owner expenditures with no differentiation by parameter type. Notice that time on the x-axis is normalized from 0% representing the beginning of design and procurement to 100% reflecting the end of construction. The y-axis on the left side represents the normalized value of owner commitments from 0 to 100% complete. The vertical shaded bars represent the significance level (α) between the successful and less-than-successful projects. All shaded bars below 0.10 (far right y-axis) represent a statistical difference between the two outcome categories. Note that this variable is a predictor of project outcome from about 30 to 55% project complete and 70 to 98% project complete. Notice that the slope of the less-than-successful project curve is steeper at the beginning of the project and reduces over a longer period of time at the end compared to the successful projects. This reveals that owners on the less-than-successful projects were expending more resources per unit of time while not making significant progress to project completion.

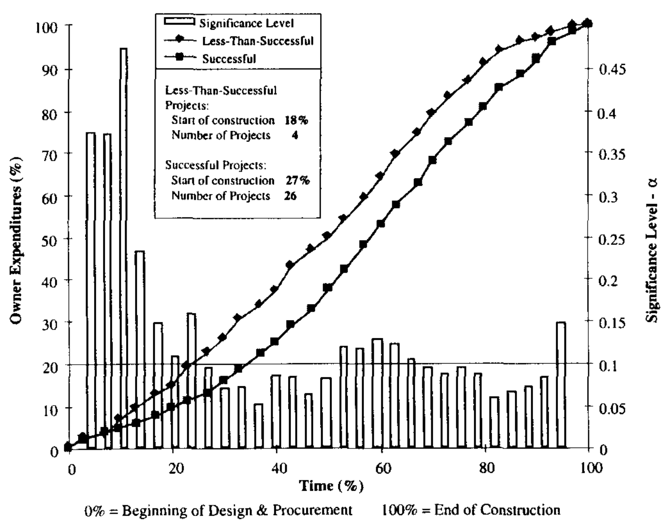

FIG. 1. Owner Expenditures for All Projects (No Differentiation by Parameter Type)

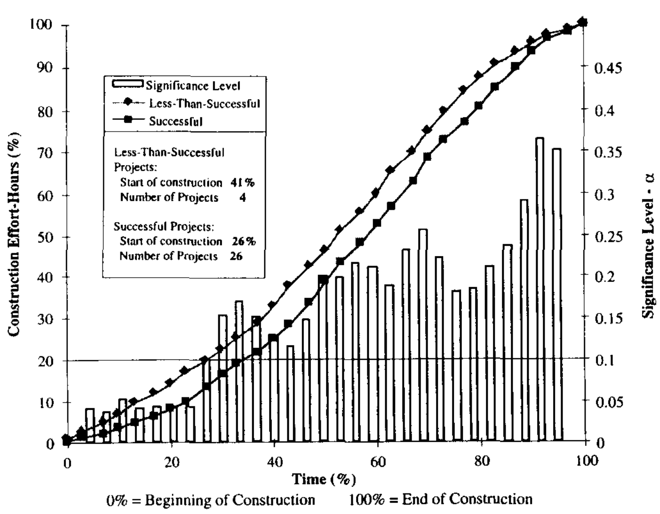

FIG. 2. Construction Effort-Hours for All Projects (No Differentiation by Parameter Type)

Fig. 2 shows the S-curves for actual construction effort-hours with no differentiation by parameter type. Here, this variable is a predictor of the project outcome during the earlier part of the construction phase (i.e., from 0% construction complete to approximately 30% construction complete). Again, it appears that the resource expenditure rate is higher for the less-than-successful projects compared to the successful ones. This may indicate that resources are not being expended efficiently on the less-than-successful projects because of inadequate project planning.

Fig. 3 shows the S-curves for invoices for material and equipment with one project parameter, contractor projects. This variable appears to be a strong predictor between 20% to approximately 70% project complete (notice that the alpha value shown by the shaded bars is less than 0.05 in this region). In this case, the contractor is receiving a larger amount of invoices for material and equipment during the middle third of the project compared to successful projects. This may indicate that the contractor is requiring materials and equipment

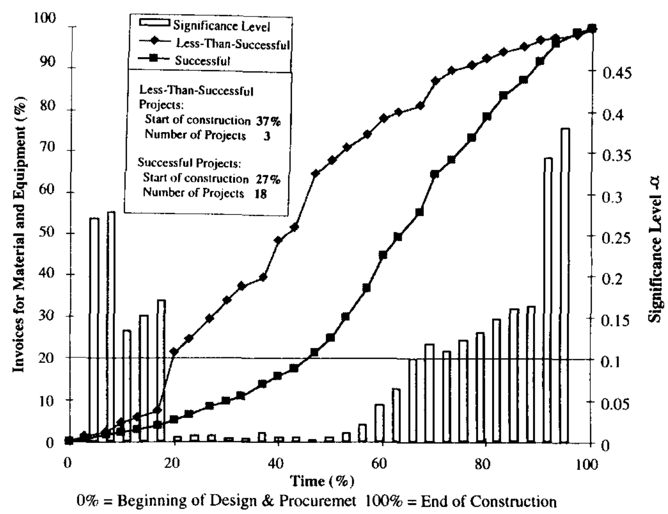

FIG. 3. Invoices for Material and Equipment for Contractor Projects (Differentiation Based on One Project Parameter)

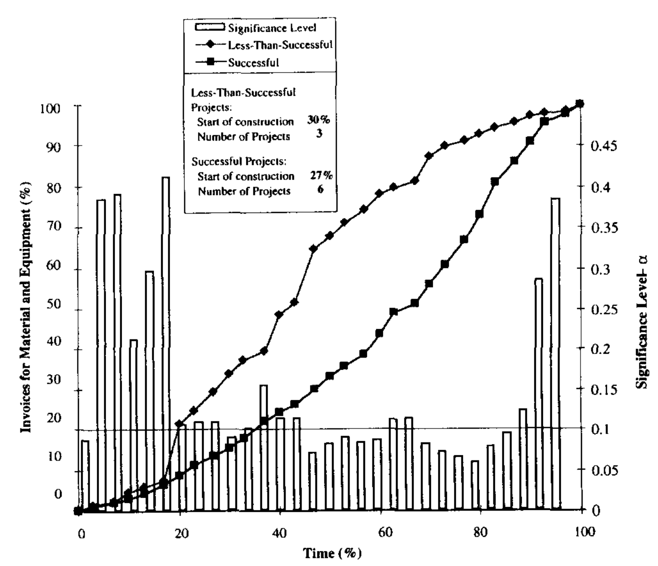

FIG. 4. Invoices for Material and Equipment Process Projects and Lump Sum Construction Contract (Differentiation Based on Two Project Parameters)

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TABLE 1. Continuous Predictive Variables Analyzed

Continuous variable (1)	All projects (2)	Lump sum projects (3)	Reimbursement cost projects (4)	Process projects (5)	Process projects and lump sum (6)
	Project Parameters				
(a) Owner					
Owner expenditures	X[a]	X	X	X	X
Cost of owner project commitments	X	X	—	X	X
Project cost percent complete	—	—	—	—	—
(b) Designer					
Designer actual effort hours	—	—	X	—	—
Designer cost	X	X	—	X	—
Design cost percent complete	X	X	X	X	X
(c) Contractor					
Contractor expenditures	X	X	—	X	X
Number of actual construction effort hours	X	X	—	X	—
Invoices paid by contractor	—	X	—	—	—
Contractor's commitments	X	X	—	X	—
Construction percent complete	—	X	X	X	—
Cost of contractor project commitments	X	X	—	X	X
(d) Combination of Owner/Contractor					
Invoiced construction costs	X	—	X	X	X
Total commitments for material and equipment	X	X	—	X	X
Invoices for material and equipment	X	X	—	X	X
Paid by construction costs	X	X	X	X	X

[a]The X's indicate that the variable for that given parameter demonstrated a statistically significant difference between the successful and less-than-successful outcome categories.

too far in advance possibly ordering the incorrect material and/or equipment.

Fig. 4 shows the S-curves for invoices for material and equipment with differentiation based on two project parameters: (1) process projects; and (2) lump sum construction contract. Notice that as greater differentiation is made (in this case, data are sorted by all process projects involving a lump-sum contracting approach), less data are available for analysis. In this instance, there are only three less-than-successful and six successful projects in the database. Even at these levels, it is still possible to perform hypothesis testing by using a small sample size. Note that this variable is a predictor of project outcome between about 45 and 60% and 70 and 90% project complete. It is interesting to observe that the predictive capability of this variable when considering only process projects using a lump sum construction contract is slightly different compared to contractor projects (refer to Fig. 3).

Hence the predictive capability of each continuous variable changes depending on the project phase and project characteristics selected. As a practical matter, if a project manager is working on an oil refinery where the construction contract is reimbursable cost and the project size is under $50 million, then it would be appropriate to use S-curves that most closely characterize that project as opposed to using more generalized project data.

Several other variables were predictors of project outcome based upon specific project parameters. Table 1 identifies the 16 variables that were analyzed in detail; a sufficient amount of data was not available to analyze the remaining 60 variables. Fifteen of the 16 variables had predictive capability.

Real-Time Project Control Charts

Based on the data in the database and the plots in the previous section, it is apparent that there are several individual continuous variables that are predictors of project outcome. If only those portions of the S-curves were plotted on a separate graph for each variable where a statistically significant difference exists between the ''successful'' and ''less-than-successful'' projects, then the concept of the real-time control chart is created. The CAPP program allows the user to identify those variables that are significant for predicting a project's outcome and plots them on a single graph; thus eliminating much of the insignificant curve information.

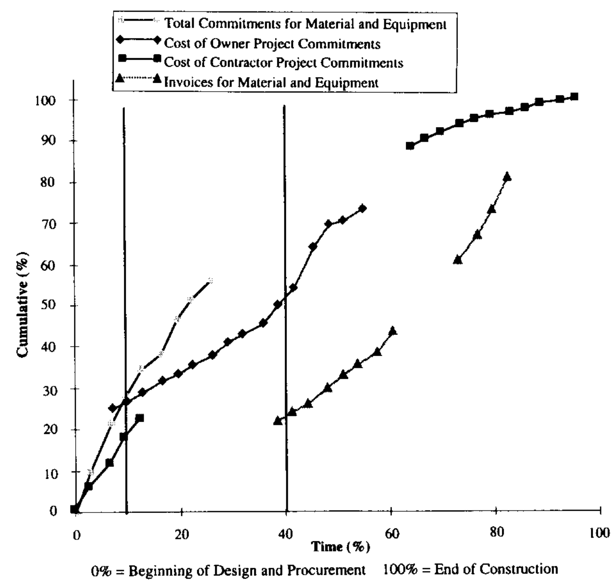

FIG. 5. Real-Time Control Charts (All Process Projects Using Lump Sum Construction Contract)

Fig. 5 shows portions of the ''successful'' S-curves for four continuous variables found to be predictors of project outcome for process plant-related projects using a lump sum construction contract approach. The four variables are: (1) total commitments for material and equipment; (2) cost of owner project commitments; (3) cost of contractor project commitments; and (4) invoices for material and equipment.

Notice that the predictive variables change throughout the life of the project. Referring to Fig. 5 at 10% project complete, there are three variables that are predictors of project outcome

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(total commitments for material and equipment, cost of owner project commitments, and cost of contractor project commitments). At 40% project complete, there are only two variables that are predictors of success (cost of owner project commitments—which was also significant at 10% complete—and invoices for material and equipment).

PRACTICAL APPLICATIONS

Preproject Planning

Individual continuous variables can be used for both preproject planning as well as project assessment from the start of detailed design through completion of construction. Fig. 6 shows the designer project cost for all projects with a successful project outcome in the database. Project managers can use this S-curve to compare their planned budget for designer cost on a particular project. If the planned curve is significantly different from the historical curve, then the project manager can make modifications to the plan to provide for a closer rate of expenditures to mimic that of a successful project.

During Project Execution

Furthermore, these curves can be used to assess and monitor the performance of a project as it progresses to determine if it is tracking according to a successful project. Fig. 7 shows the S-curves for owner expenditures for successful and less-than-successful projects.

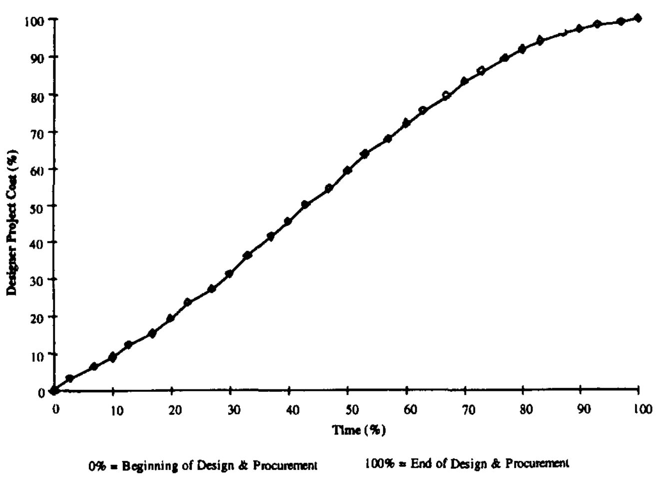

FIG. 6. Designer Project Cost for All Projects

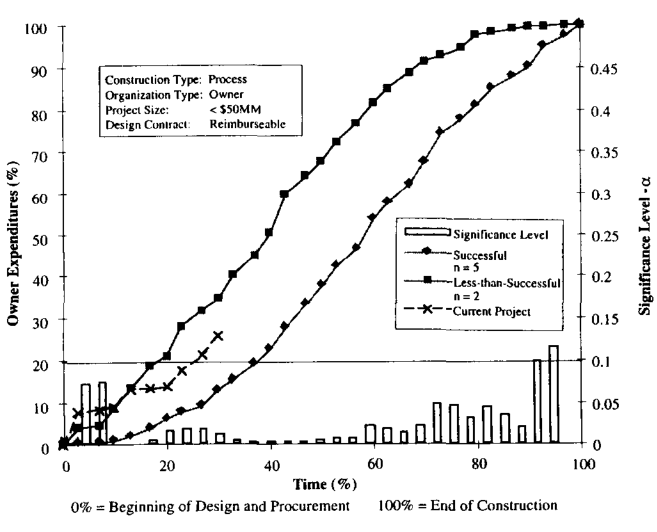

FIG. 7. Owner Expenditure Curves Used to Track a Project

Individual Variables

In Fig. 7, note that the actual project values start out tracking slightly above the less-than-successful curves and begin in the direction of the successful curve at approximately 18% project complete. At 30%, the actual project value is between the successful and less-than-successful project curves. In this case, it is difficult to tell whether this project is in trouble or not; consequently, engineering judgment will need to be used to make this final decision as to whether corrective action will be necessary and what corrective action is required. The basic premise is that the further away from the successful curve and the closer to the less-than-successful curve, the greater the chances of experiencing a less-than-successful project.

Real-Time Project Control Charts Involving Multiple Variables

An example can demonstrate the use of the real-time project control chart. Since most of the data collected were process plant projects using a lump sum construction contract, an example is provided using these project characteristics. A project manager is interested in assessing the likelihood of achieving a ''successful'' project—one that meets or exceeds the owner's budgetary and schedule expectations. The project is a $50 million process plant-related project using a lump sum construction contract. The anticipated project duration is 24 months where five months have already been completed.

The project manager wants to determine the project outcome based using the real-time project control chart (refer to Fig. 8). The process first involves calculating the project percent complete (x-axis value) by dividing the number of months completed by the planned project duration—this happens to be approximately 20% (5/24) (note 1 in Fig. 8). Next, the variables that are predictors at 20% project complete are identified. In this case, there are two variables that are predictors: (1) total commitments for material and equipment; and (2) cost of owner project commitments (note 2 in Fig. 8).

The practical use of the control chart will be demonstrated using only one of the variables—cost of owner project commitments. The percent complete value for commitments (y-axis) is calculatd by dividing the actual owner project commitments to-date by the total anticipated owner project commitments; two scenarios are considered in the following.

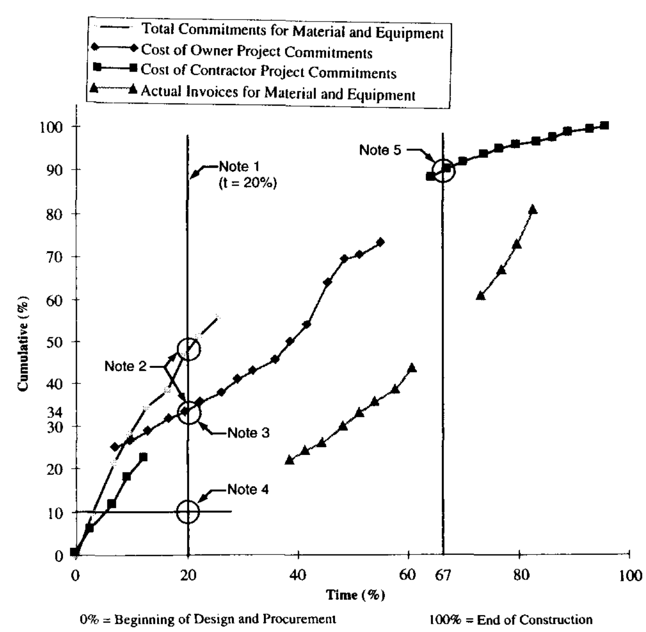

FIG. 8. Real-Time Project Control Charts (All Process Projects Using Lump Sum Construction Contract

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In the first scenario, the actual owner project commitments to date equals $17,000,000 while the total anticipated owner project commitments for the entire project equals $50,000,000. Thus, the ratio of $17,000,000 to $50,000,000 is 34%. This means that 34% of the commitments have been made at this point in the project. The next step is to plot this value on the real-time control chart and compare it to the expected value for a successful project.

Once the appropriate value is plotted (x-axis = 20%; y-axis = 34%), one can clearly see that the point lies on the curve predicting a successful project outcome (refer to note 3 in Fig. 8). This means that the project is tracking similar to a successful project outcome at this point in time.

It should be noted that there is some tolerance associated with each curve since they are formed by averages of many projects; thus, if this month's value is not exactly on the line, the project may still be successful when it is completed. The chances of not meeting project expectations, however, increase as the point moves further away from the success curve.

In a second scenario, the cumulative actual owner project commitments equals $5,000,000. The percent complete of commitments is now $5,000,000 divided by $50,000,000 or 10%. Thus, at 20% project complete, the owner has only committed 10% of the budget. After this point is plotted on the real-time control chart, it is apparent that the project is not tracking according to a successful project because of the large distance away from the success curve (refer to note 4 in Fig. 8). This implies that the anticipated project outcome will probably not meet the budgetary and schedule expectations unless corrective action is taken. There are many sources of information to determine what the problem(s) is and appropriate corrective action. One potential source for identifying corrective action developed by the Predictive Tools task force is the Predictive Tools Road Map (Arneson 1994). The Road Map can be used to help identify potential causes of a problem and provide references for identifying possible solutions.

FUTURE DIRECTION

The future direction involves addressing the limitations described previously. Of immediate necessity is to collect more data to identify other key variables and improve the reliability of the existing results.

To reduce the amount of engineering judgment to interpret whether the project is tracking similar to a less-than-successful project or not, quantitative models can be developed for predicting success at any phase using real-time control charts. A discrete choice modeling approach may be used because of the discrete nature of the project outcomes (i.e., successful or less-than-successful). Predictive models can be developed at several phases of the project (e.g., 10, 20, 30, 40, 50, and 75%); a generic model for predicting project success at 10% complete is shown as

$$\text{probability of success}_{10\%} = B_0 + B_1X_1 + B_2X_2 + B_3X_3 \quad (1)$$

In the preceding example, describing the practical application of the real-time project control charts, a one variable model was developed for predicting project success at the 67% completion point. Fig. 8 shows that the cost of contractor project commitments variable is the only predictor at 67% project completion for process plant projects using a lump sum construction contract (note 5 in Fig. 8). A regression model has been developed using the JMP statistical software package for discrete choice modeling. The following equation, which has not been adjusted for a choice-based bias, represents the discriminant function

$$y = -9.42 + 12.9\cdot(\text{cost of contractor project commitments, } 0\text{–}100\%) \quad (2)$$

The value from this discriminant function is then used in the logistic function that allows any value of y to range between negative and positive infinity on the x-axis and between 0 and 1 on the y-axis. The y-axis represents the probability of achieving a successful outcome. The logistic function is shown as

$$\text{probability of successful outcome} = e^{y}/(1 + e^{y}) \quad (3)$$

For more detailed information about this modeling approach, refer to Aldrich and Nelson (1984) or Ben-Akiva and Lerman (1985). To illustrate the use of this method, suppose that a project is 67% complete, the normalized value of the cost of contractor project commitments is 50% and the project manager wants to know the probability of achieving a successful project outcome. (It should be noted that the normalized value for this variable should be around 90% complete to achieve a successful outcome.) First, calculate the value of y at 67% project completion [$y = -9.42 + 12.9\cdot(50\%) = -2.975$].

Using the logistic equation, the discriminant value, y, is inserted into the logit function to obtain the probability of a successful outcome as follows:

$$\text{probability of successful outcome}_{67\%} = e^{-2.975}/(1 + e^{-2.975}) = 5\% \quad (4)$$

From this model, it can be seen that there is only a 5% of this project achieving a successful outcome. Fig. 9 shows a curve reflecting the probability of success for different values of this variable. Note that as the amount of commitments increases, the probability of a successful outcome increases as well. The benefit of using this regression approach is that models can be generated using variables found to be predictors at that point in time. Project managers will be able to obtain a probability of success at any point in the project. In an age of information overload, this can enable a project manager to focus on the significant few variables as compared to the insignificant many variables.

In this example, the predictive model is used in an absolute sense; these types of models can also be used in a relative sense (i.e., sensitivity or "what if" analysis). For example, what if the project manager changes commitments by 10% for the next reporting period—how will this affect the probability of a successful outcome? The same question may be asked of other variables in the model and one can determine which of the variables is more sensitive to achieving a successful project outcome.

A note of caution: the example model provided in (2) illus-

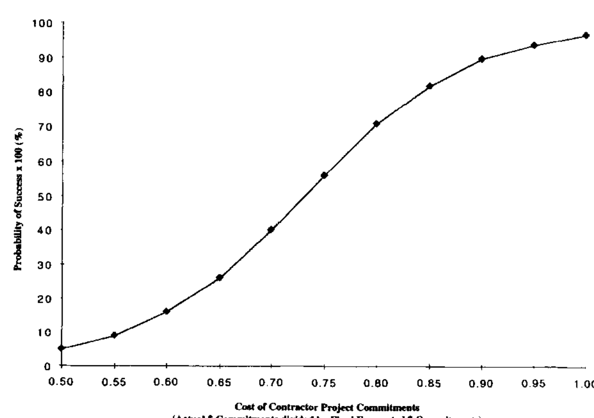

FIG. 9. Probability of Success at 67%: Cost of Contractor Project Commitments (All Process Projects Using Lump Sum Construction Contract)

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trates how continuous data can be used to develop quantitative models to predict the probability of success at specific points in time. As a practical matter, this model will unlikely be used by a project manager as a means of an early indication of project success because the project is already 67% complete. Ideally, models developed early in a project's life (i.e., 10, 20, 30, and 40%) enable corrective action to be taken early enough to have an effect on the project outcome.

On the other hand, other relationships not investigated that appear worthwhile include:

- Percent engineering complete compared to percent construction complete
- Percent procurement complete compared to percent engineering complete
- Percent money committed to equipment compared to percent project time expended
- Percent drawings issued compared to percent project time expended
- Percent project duration over (under) compared to percent project complete
- Percent project budget expended compared to percent oject complete
- Percent over (under) budget compared to percent project complete
- Percent complete compared to percent project time expended

LIMITATIONS

Collecting continuous data on already completed projects was challenging for several reasons: (1) past project records were not in the format necessary to fill in the data collection tool; (2) knowledgeable persons had already been assigned to other projects and were difficult to interview; (3) not all continuous data were collected on each project, and (4) the time commitment was significant for each organization. In addition, it appears that some of the 76 variables initially proposed as predictors of success may in fact not lend themselves to the type of analysis presented in this paper. For example, it is difficult to conceive that first-aid cases; facilities; days lost due to weather; days lost due to strikes; overtime work; cost and quantity of remaining change orders; schedule impact of variance/trends; among others, will independently predict the cost and schedule outcomes of a project. These variables were measured by the number of occurrences or frequency. A large amount of data will have to be collected to further investigate whether the variables can contribute to predicting project outcomes.

A sufficient amount of data, however, was collected to demonstrate the concept of using continuous or time-dependent variables as predictors or project cost and schedule outcomes.

There are several limitations to this research investigation. First, there was a limited amount of data for 60 of the 76 variables that made it difficult to identify other potential continuous variables that may be predictors of project outcome. Second, the definition of project success had to be narrowed because the scope for other measures such as safety and quality were beyond the scope of this research investigation. Third, many of the curves presented herein were developed using a small sample of data—more data would be helpful in further establishing a variable's predictive abilities.

Fourth, to be even more precise, real-time project control charts and individual variable curves should be developed based on company and project-specific data. Currently, the database is very general, and a robustness analysis should be performed to assess its applicability to project characteristics of many types. Fifth, using the real-time control charts requires the estimated total continuous variable value (y-axis) and the estimated duration (x-axis) be accurate as the plotted coordinate x and coordinate y are a ratio of actual to estimated. Thus, if the estimated values are smaller, the calculated percentage will be under estimated (to-date three months complete, estimated duration 10 months when it should have been estimated at five months; 3/10 30% versus 3/5 60%). On the other hand, if the estimated values are larger, the calculated percentage will be overestimated (This situation is probably the more realistic scenario that occurs in industry; being overly optimistic, therefore, under estimating the continuous variable value and duration of the project). The true impact occurs when a project manager believes the project is tracking on the path to success when actually it is not. Sixth, it is desirable to quantify how close to the successful curve warrants no corrective action and how far from the successful curve that necessitates corrective action.

CONCLUSIONS

This paper has presented a unique approach for real-time project control that can assist project managers in better predicting the success of a project prior to its completion. Data were collected on 76 continuous or time-dependent variables for successful and less-than-successful projects. Statistical analysis procedures were used to identify variables showing a significant difference between the S-curves for each type of project outcome. Results showed that it was possible to predict outcome based on continuous variables and that the predictive ability of a variable changed depending on the type and phase of the project. A computer program, CAPP, was developed to make the calculations transparent to the user. This approach can be used by upper and middle management as a benchmarking tool for predicting project performance before a project begins (especially during preproject planning). Also, this control method can be used for early warning detection for predicting potential problems meeting budget and schedule expectations during the design and construction of a project.

It should be pointed out that this paper has described a process by which continuous variables can be collected, analyzed, and predictions of project success made. This process represents the foundation to further data collection and analysis using continuous variables to predict project success. This paper by no means has identified nor demonstrated the only continuous variables that may predict project success. Furthermore this paper has not identified nor demonstrated the only form in which quantitative models can be developed.

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APPENDIX I. LIST OF CONTINUOUS VARIABLES

Designer cost
Designer effort hours

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Cost of change orders
Construction percent complete
Quantity of changes
Design percent complete
Number of contractor team personnel
Number of actual construction effort hours
Owner expenditures
Invoiced construction costs
Project cost percent complete
Designer planned effort hours
Planned construction percent complete
Cost of contingency expended
Cost of contractor project commitments
Total commitments for material and equipment
Invoices for material and equipment
First-aid cases
Planned design percent complete
Invoices paid by contractor
Planned designer cost
Paid construction costs
Contractor expenditures
Planned project cost percent complete
Contractor's commitments
Number of planned construction effort hours
Recordable incident rate
Cost of owner project commitments
Planned owner expenditures
Planned contractor expenditures
Cost of variance/trends
Procurement percents complete
Construction drawings
Owner effort hours
Injuries resulting is lost work days
Contractors' commitments for engineering equipment and long lead items
Severity rate
Recordable incident rate
Overtime work
Total commitments for engineering equipment and long lead items
Planned invoices for material and equipment
Construction hours earned
Owner personnel actual quantity
Cost of change orders
Quantity of change orders
Cost of rework due to designer
Planned construction drawings
Less retention held
Planned procurement percent complete
Cost of rework due to owner
Number of personnel turnover
Injuries resulting in restricted work days
Severity rate
Cost of remaining change orders
Quantity of remaining change orders
Shop drawings
Schedule impact—owner approved
Quantity of request for proposals
Owner's direct commitments
Cost of rework due to vendors
Days lost to weather
Cumulative days lost to weather
Owner personnel planned quantity
Schedule impact of variance/trends
Cost of rework due to contractor
Owner's commitments for engineering equipment and long lead items
Cost of requests
Planned owner effort hours
Schedule impact—contractor perceived
Impact of pending change orders
Cost of rework due to field conditions
Number of days remaining
Fatalities
Days lost due to strike
Planned overtime work
Planned shop drawings

APPENDIX II. REFERENCES

Aldrich, J. H., and Nelson, F. D. (1984). *Linear probability, logit, and probit models*. Sage, Beverly Hills, Calif.

Arneson, J. R. (1994). "A framework to organize and classify predictive tools for construction project managers," MS thesis, Univ. of Wisconsin–Madison, Madison, Wis.

Ben-Akiva, M., and Lerman, S. R. (1985). *Discrete choice analysis: theory and application to travel demand*. MIT Press, Cambridge, Mass.

Lawrence, S. L. (1995). "Development of a predictive tool for continuous assessment of project performance," MS thesis, Univ. of Wisconsin–Madison, Madison, Wis.

Russell, J. S., and Jaselskis, E. J. (1996). "Continuous assessment of project performance." *Spec. Publ. 107-02*, The Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.

Russell, J. S., Jaselskis, E. J., Lawrence, S. L., Tserng, H. P., and Prestine, M. T. (1996). "Development of a predictive tool for continuous assessment of project performance." *Res. Rep. 107-12*, The Constr. Industry Inst., Univ. of Texas at Austin, Austin, Tex.

J. Constr. Eng. Manage., 1997, 123(1): 64-71