Technical Management Notes

Schedule Monitoring of Engineering Projects

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Abstract—**"Progress plotting" is a tool for monitoring, reporting, and controlling the progress of time-critical projects. It helps distinguish between minor schedule slips and problems that call for serious management intervention. It also serves to evaluate planning accuracy on previous projects. "Progress" is shown by plotting the actual time used on a project against the completed percentage of the critical path. "Control lines" in the plotting space indicate probabilities of completing the project on schedule. If the progress line crosses a low probability control line, managers may want to intervene and bring the project back on schedule. Crossing a high probability control line means an early finish may be anticipated with confidence. The progress plot is comparable to the process-control chart used in manufacturing settings. Like the control chart, it uses simple, familiar measures to put current performance into an historical (statistical) context that can be understood by everyone on the project. It thus serves as a focus for discussion and a source of continuous feedback to the project team, project manager, and higher management.**

Introduction

This paper presents a tool for monitoring, reporting, and controlling the progress of time-critical projects. The "progress plot," built from standard PERT network data, gives engineering managers the kinds of project control that are usually associated with process-control charting and a manufacturing process:

- a clear, simple, visual comparison of current performance versus expected performance,
- distinction between tolerable deviations from plan and developments that may call for management intervention, and
- an easily-interpreted progress report for higher management and the entire project team.

Progress plotting is useful for comparing different projects with respect to planning accuracy.

During time-critical projects—developing new products for a highly competitive market, for instance—strong interest centers on the likelihood of finishing on schedule. Accurate and current information on progress relative to schedule is crucial for the scheduling of engineering resources, manufacturing operations, product announcements, and customer shipments. Once a project is underway, however, the probability of finishing on schedule is not easily read from traditional PERT or GANNT charts. The progress plot, however shows these probabilities at a glance.

Recent research suggests that schedule goals are more often met when:

- engineers, line managers, and high level managers all participate in goal setting,
- managers use both formal and informal monitoring mechanisms,
- managers provide timely and well-targeted responses to development problems, and
- a high level of communication is maintained both within and between engineering groups.

(See, e.g., [1], [7], and [8]). On projects where the most critical engineering goals are schedule goals, the progress plot serves effectively to focus all of these activities.

An Example Progress Plot

Fig. 1 shows a progress plot for a completed project. The horizontal axis represents time. The original plan called for project start at t_0 and completion at planned completion time t_{PC}. Time t_{PC} equals the critical path (CP) from a task/event network such as a PERT chart. The vertical axis represents project progress, as a percentage of the CP (as explained below).

Had this project gone as planned, the actual progress line would lie on the original plan line, reaching 100-percent completion at t_{PC}. Instead, the project ended at actual completion time t_{AC}. Filled circles are planned CP events, open circles are actual event occurrences. Solid lines connecting these circles reveal a continually increasing discrepancy between actual progress and planned progress.

Control lines (explained below) warned, early in the project, of a probable late finish. At t_l the probability of finishing by t_{PC} was 0.25, and falling (i.e., the actual progress line crossed the $p = 0.25$ line at t_1). By t_2, the project only had a 0.01 chance of finishing on time.

Note that all segments of the actual progress line slope *less* than the original plan line. This suggests strongly that management consistently underestimated task times (or else consistently used inadequate resources). The smoothness of the progress line, however, shows that progress was relatively continuous and that the expected critical path was in fact the actual critical path.

A Metric for Project Progress

In engineering projects, no single metric adequately represents project "progress" for all purposes. Different progress measures might reflect the current proportion of

- design problems solved,
- design phases (or stages) completed,
- total person/hours used,
- allocated funds spent.

or other things. However, if completion date is the major concern, we may represent the project with a single path, a series of consecutive tasks, where current progress is a point on the path. Figs. 2 and 3 show how this path is derived for the progress plot.

Fig. 2 is a top level PERT network for a new product development project. Numbered circles are events and arrows are tasks that lead from event to event. Starting event #1, for instance might be "Product Requirements Defined" and final event #15 might be "First Customer Shipment." Other top level CP events could be, perhaps, "Logic Design Specs Completed," Simulated Timing Verified," "Prototype Assembled," and so on. For complex projects, managers will also use lower level plans of activities and events that make up each task on the top level plan.

Fig. 2 also gives an estimated completion time and variance for each task, in weeks (variances are inside parentheses). These come from standard PERT methods: if $t_{i,j}$ is the task time needed to go from event i to event j, then the expected task time, $E(t_{i,j})$ and the

Manuscript received April 13, 1987; revised August 15, 1987.

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IEEE Log Number 8717862.

0018-9391/88/0500-0108$01.00

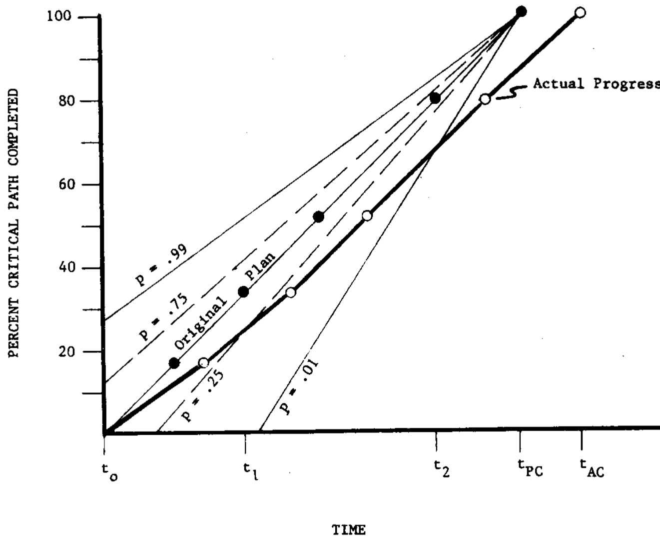

Fig. 1. An example progress plot.

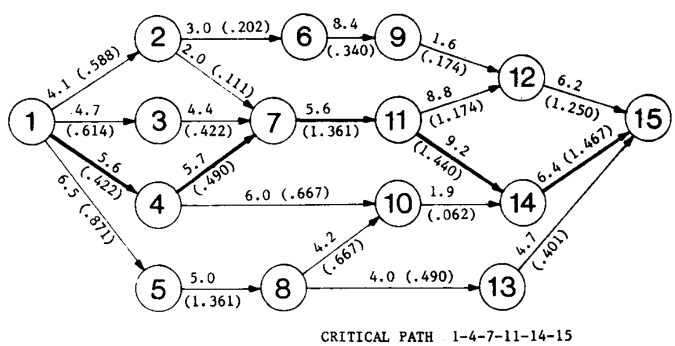

Fig. 2. The PERT activity/event network for example calculations.

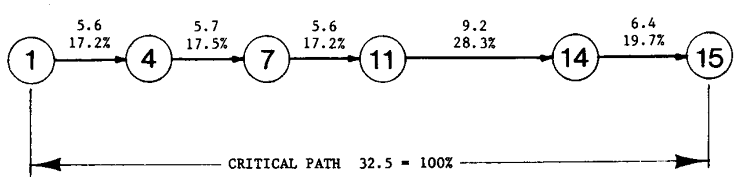

Fig. 3. The critical path (CP) for progress plot examples.

estimated variance of the task time probability distribution $\sigma^2_{i,j}$ are derived as

$$E(t_{i,j}) = \frac{a + 4m + b}{6} \tag{1}$$

and

$$\sigma^2_{i,j} = \left(\frac{b - a}{6}\right)^2 \tag{2}$$

where

- a estimated shortest possible task time,
- b estimated longest possible task time,
- m estimated most likely task time.

In task 1, 2 for instance, $a = 2$, $b = 6.6$, and $m = 4$ weeks. (For more on traditional PERT methods, see an introductory text on quantitative management or PERT itself, e.g., [4], [9], or [10]). Estimated task times are the basis of the progress plot's original plan line (this section). Tasks variances make possible control lines (following sections).

Analysis of the estimated task times reveals a 32.5-week CP linking events #1, 4, 7, 11, 14, and 15. Fig. 3 shows the CP by itself, an $E(t_{i,j})$ for each CP task, each task's contribution to the CP, expressed as a percentage of the total CP. The progress plot framework is built from these data. Horizontal axis segment $t_0 - t_{PC}$ equals CP length (here, 32.5 weeks). The vertical axis is scaled from 0 to 100 percent. The original plan lines runs from point (t_0, 0 percent) to point (t_{PC}, 100 percent). CP events appear on this line at the event's estimated occurrence (horizontal axis) and critical path location (vertical axis). These are the filled circles in Fig. 1. Actual progress is tracked by plotting the actual completion times of CP events, as total time after t_0 (horizontal axis) and *original* CP percentages for those events (vertical axis). These are the open circles in Fig. 1.

Fig. 4 shows how the progress plot reveals planning mistakes. All segments of actual progress line A slope more steeply than the original plan line. All tasks were thus completed under the planned (estimated) time. By contrast, Line B and Fig. 1 illustrate consistently underestimated task times. Line C shows the effects of overestimating some task times and underestimating others. The extent to which the actual progress line either deviates from or "hugs" the original plan line represents planning accuracy. Line D shows what happens when tasks *not* on the original CP took longer than planned and became CP tasks. This kind of planning error makes a horizontal line segment in the progress line (there is a real time gap between the end of one CP task and start of the next).

Actual progress lines of several projects, current or historical, can be plotted together by scaling the horizontal axis as "Percentage of Original CP Time Actually Used" instead of absolute time. All projects then, regardless of length, will have the same t_{PC} and the same original plan line.

Control Lines for the Progress PLOT

The original plan and actual progress lines are descriptive statistics. Actual time used is compared to planned usage. They can be derived without a full PERT network: "phase transition points" or some other locally used series of planned and actual event dates will suffice, as long as the sum of the segments equals planned project length. However, the progress plot's control value is enhanced if task time variances are used to make probabilistic inferences about the actual project completion time.

As illustrated in Fig. 1, these inferences follow when actual progress crosses a control line. Each control line is associated with a probability—the probability that the project reaches completion on or before t_{PC}. Control lines for any number of p values between 0 and 1.0 may be calculated, but the plot is clearer if only a few are plotted, e.g., $p = 0.01$, $p = 0.25$, $p = 0.75$, and $p = 0.99$. The original plan line is also the $p = 0.50$ line.

The form and location of control lines depend on the assumptions one makes about the project. Five assumptions however, underlie *all* control line methods. These five are usual in PERT applications.

[Assumption 1]: Task times are independent (actual time used for any task has no effect on estimated task time or variance of any other task).

[Assumption 2]: Probability distributions for task times have means and variances given by (1) and (2) above.

[Assumption 3]: Probability distributions for the *sums* of individual task times are approximately normal with means and variances as follows:

$$\mu_T = \sum E(t_{i,j}) \quad (3)$$

$$\sigma_T^2 = \sum \sigma_{i,j}^2 \quad (4)$$

for all tasks i, j included in the total.

Assumption 3 means that the central limit theorem applies to sums of expected task times. Thus, no other assumptions are needed about the *shapes* of individual task time probability distributions, where interest centers on task time sums.

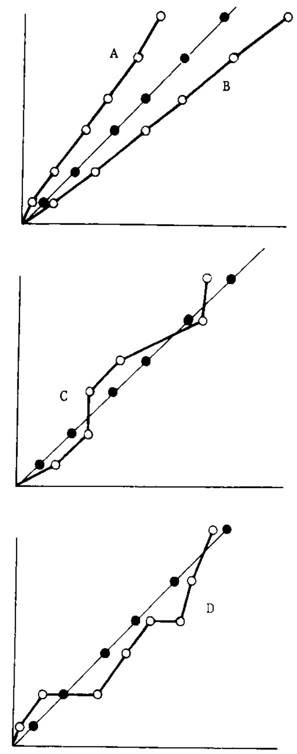

Fig. 4. Four types of actual progress lines.

[Assumption 4]: Estimated completion time for the project equals the sum of estimated critical path task times.

Thus, the original plan line shows each CP task ending at the next task's beginning. Note, however, that time may pass between *actual* completion of one CP task and start of the next. In other words, control lines (based on the original plan) are valid even if planned non-CP tasks actually enter the CP.

[Assumption 5]: During the project, estimates a, b, and m for each task do not change.

When the actual progress line crosses a control line, e.g., the $p = 0.25$ line, the probability of completing the project by t_{PC} or sooner is 0.25, *as long as the original a, b, and m estimates still apply.* However, if the manager now deviates from the original plan—applying more or less resources than originally planned for a specific task, for instance—the original control line probabilities are not valid during that task.

Should new control lines be drawn when resources are shifted, or when estimates a, b, and m otherwise changes? If the changes represent corrective actions for one CP task, to get the project "back on schedule," the original control lines should remain. They will apply again when the "unusual" task is completed. If, however, a, b, and m estimates change for several CP tasks, new control lines should be drawn, since the old ones will not be valid again. And, if changes in a, b, and m during the project alter the CP itself, the original plan line may stay in place, as far as it represents completed tasks, and a revised original plan line can be drawn to the *new* point (t_{PC}, 100 percent).

Given Assumptions 1–5, we can choose one of several methods for plotting control lines. So as to contrast the different methods, each will be illustrated with the data from Fig. 2.

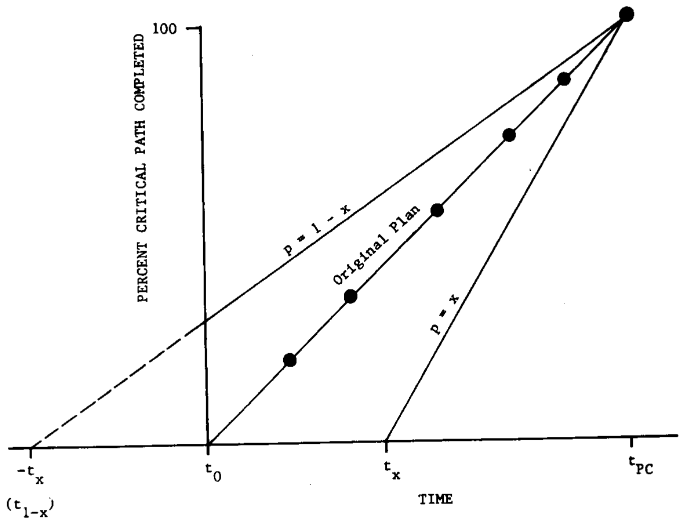

Fig. 5. Elements of progress plot construction when CP variances are proportional to task lengths.

Control Line Method 1: CP Variances Proportional to Task Length

The simplest approach to control lines may be called the "Proportional CP Variances" method. It requires two more assumptions.

[Assumption 6]: The likelihood of non-CP tasks intruding on the CP is so small that only CP tasks need be considered when constructing control lines.

[Assumption 7]: Variances of individual task time probability distributions are proportional to task length.

Individual task time variance estimates (which may or may not conform exactly to Assumption 7) are used only to obtain an estimated variance for *total* project completion time. This variance is then "redistributed" among individual tasks as if Assumption 7 were true. (If Assumptions 6 and 7 are not tenable, a different control line method must be used).

Fig. 5 shows how control lines are drawn. Under this method, each is a straight line from a point on the horizontal (time) axis, point t_x, 0 percent, to the project end, (t_{PC}, 100 percent). For the control line at $p = x$, the value of t_x is computed as:

$$t_x = z_x \sqrt{\sigma_T^2} \tag{5}$$

where z_x is the value under a unit-normal distribution, above which proportion x of the distribution lies, and

$$\sigma_T^2 = \sum \sigma_{i,j}, \qquad \text{for all tasks } i, j \text{ on the CP.}$$

z_x values come from a unit-normal table. For $x = 0.01$, for instance, $z_x = 2.326$ and for $x = 0.25$, $z_x = 0.675$. For the CP and other data shown in Fig. 3:

$$\sigma_T^2 = 0.422 + 0.490 + 1.361 + 1.440 + 1.467$$
$$= 5.180$$

and, for $x = 0.01$:

$$t_x = (2.326)\sqrt{5.180}$$
$$= 5.29 \text{ weeks.}$$

Similarly, t_x for $x = 0.25$ is $(0.675)\sqrt{5.180} = 1.54$ weeks.

Control lines for probabilities greater than 0.50 lie above the original plan line, intersecting the vertical axis at some value greater than 0 percent. The horizontal axis coordinate of these is found, as Fig. 5 suggests, by extending the axis to the left of t_0, where negative values represent an actual start before planned start at t_0.

From the unit-normal distribution, all z values for control p values greater than 0.50 will be negative. From the unit normal distribution's symmetry, note that

$$t_{1-x} = -t_x. \tag{6}$$

Control Line Method 2: Individual CP Variances

If task time variances are clearly not proportional to task lengths (Assumption 7 is not tenable), control lines in the progress plot should be drawn by the method of "Individual CP Variances." This approach requires Assumptions 1–6, and a new assumption:

[Assumption 8]: Probability distributions for individual tasks on the top-level PERT CP are approximately normal.

Assumption 8 is reasonable if each task on the top-level PERT represents the sum of a series of tasks from a lower-level PERT.

This method is identical to the preceding, except that a new t_x is calculated at each original plan CP event. The total variance at each CP event is taken as the sum of the remaining task variances. Equation (4) is applied at *each* CP event, except that σ_T^2 (in the equation) now represents all *remaining* CP tasks. Fig. 6 shows the resulting progress plot with $x = 0.01$ and $x = 0.99$ control lines. With the example data and $x = 0.01$, for instance, $t_x = 5.29$ weeks at project start (as before). At the the next CP event, 4, σ_T^2 for the remaining CP is $5.180 - 0.422 = 4.758$ and t_x is thus $(2.326)\sqrt{4.758} = 5.07$ weeks. A t_x is calculated in this way for each CP event through the next to the last (here, event 14); the control line is offset horizontally by this amount from each of these events.

Control Line Method 3: Risky Non-CP Tasks

Engineering projects, especially those composed of several nearly independent subprojects, are often characterized by parallel and

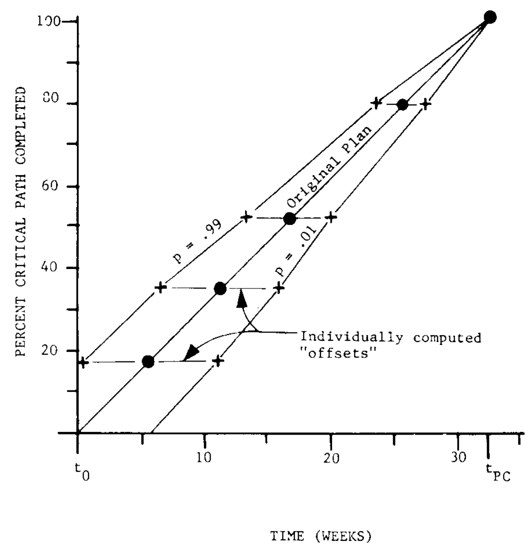

Fig. 6. Two control lines for the progress plot, constructed with the method of individual CP variances.

relatively independent activity paths which only meet at a few "nodal" events (such as "Prototype Assembled"). As long as Assumption 6 is tenable, however, CP progress adequately represents progress for the whole project. However, when task time variances are large relative to expected task times, and when one or more non-CP paths have a large variance, the manager may want to recognize non-CP risks in the progress plot.

Unfortunately, calculating expected task lengths and risks so as to reflect the entire PERT network becomes a prohibitively complex and assumption-laden undertaking in networks with more than a few events (see, e.g., [2] or [5]). For progress plotting and control line purposes, however, it is usually satisfactory to apply some elementary probability rules in order to recognize the risk of just one or a very few non-CP task intruding onto the CP.

Fig. 7 illustrates the general approach. Consider, for instance, the project plan portion shown in Fig. 7(a), covering events 11, 12, 14, and 15 from Fig. 2. The project's CP links events 11-14-15. The expected length of this CP segment is 9.2 + 6.4 = 15.6 weeks. Note that non-CP path segment 11-12-15 is nearly as long: 8.8 + 6.2 = 15 weeks. The 0.6 week difference between path segments may be thought of as "slack" time in the 11-12-15 segment. Consider also the standard deviations (σ s) for these segments: both segments have task time σ s that are large relative to the 0.6-week difference between paths:

$$\sigma \text{ of path } 11\text{-}12\text{-}15 = \sqrt{1.174 + 1.250} = 1.557$$

$$\sigma \text{ of path } 11\text{-}14\text{-}15 = \sqrt{1.440 + 1.467} = 1.705.$$

The near-criticality of path 11-12-15, and the large size of these σ's relative to the slack in path 11-12-15, suggest that control lines should reflect both path segments in Fig. 7(a). We may include the risk of path 11-12-15 entering the CP by invoking Assumptions 1-5, 8, and one new assumption about the placement of slack time in segment 11-12-15:

[Assumption 9]: Each non-CP task that contributes to the progress plot will begin at the earliest possible time.

As the time lines in Fig. 7(b) suggest, Assumption 9 puts all the slack

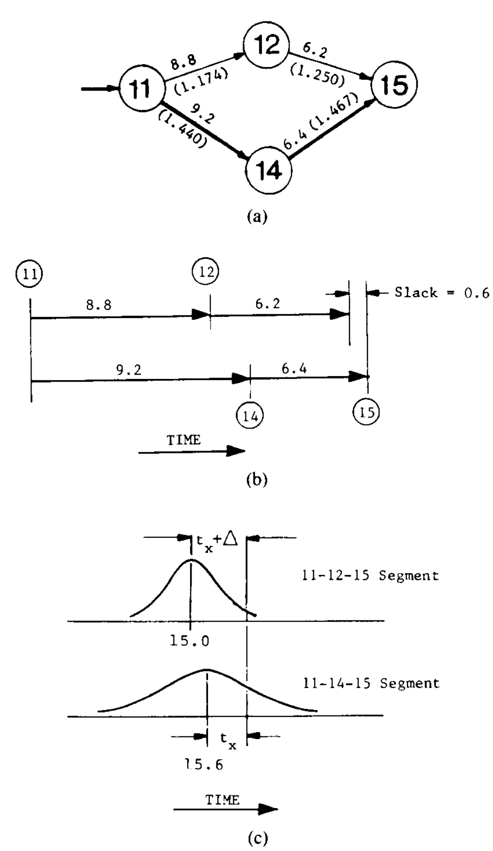

Fig. 7. Including non-CP risks in control line calculations. (a) Two path segments considered in the example. (b) Time relationships in both segments. (c) Probability distributions assumed for path segments immediately after event 11.

in segment 11-12-15 at the end of task 12-15. Other assumptions about slack are possible, but *some* assumption has to be made in order to proceed. For each control line probability x, the t_x horizontal axis "offsets" from the original plan line will now be calculated for each event, 11, 12, and 14. All offsets are of course 0 at event 15, project completion.

Consider now the situation after event 11. Each control line probability x represents:

$$x = p[(\text{Path } 11\text{-}12\text{-}15 \geq 15.6) \text{ OR Path } 11\text{-}14\text{-}15 \geq 15.6)]. \quad (7)$$

In general terms, if we let

A = the event (Path 11-12-15) $\geq$ 15.6), and
B = the event (Path 11-14-15) $\geq$ 15.6),

then

$p(A \text{ or } B) = x$, the control line probability.

Assuming that A and B are independent events (Assumption 1), elementary probability theory gives

$$x = (A) + p(B) - p(A \text{ AND } B) \quad (8)$$

where

$$p(A \text{ AND } B) = p(A)p(B).$$

Fig. 7(c) represents the probability distributions for total task time in both path segments. As indicated, the distribution for non-CP path 11-12-15 has μ_1 = 15.0 and σ_1 = 1.557. The distribution for CP

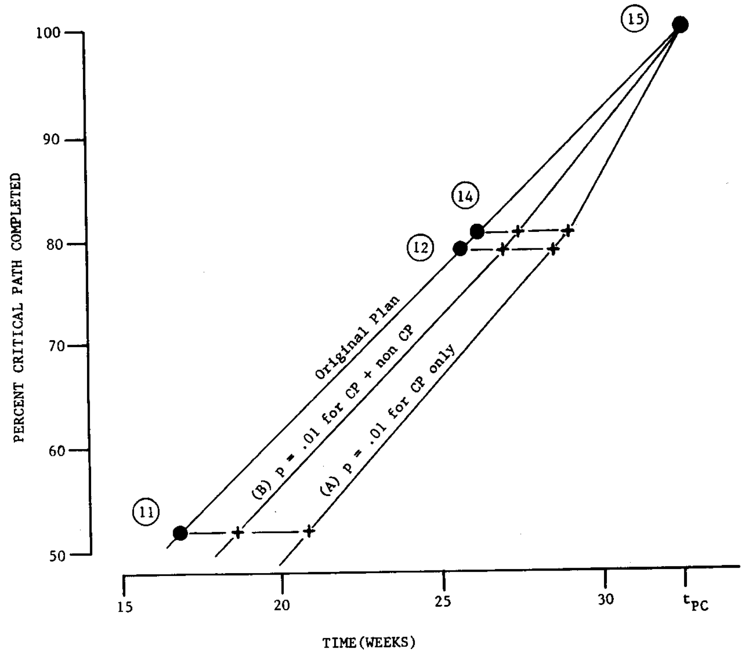

Fig. 8. Comparison of control lines at $p = 0.01$ where (A) only the CP path segment is recognized, and (B) where both a CP and non-CP segment are recognized.

path 11-14-15 has $\mu_2 = 15.6$ and $\sigma_2 = 1.705$. From Assumptions 3 and 8, both distributions will be described as $f(z)$, the standard unit-normal distribution:

$$f(z)=\frac{1}{\sqrt{2\pi}}\,e^{-(z^2/2)}. \tag{9}$$

The total area under $f(z)$ from $z = -\infty$ to $z = +\infty$ equals 1.0, and the probability that a value of random variable z falls within any interval on the z scale is the area under the curve, over that interval. In the 11-14-15 distribution, a t_x value can be converted to a unit-normal z value as:

$$z_2=\frac{t_x}{\sigma_2}. \tag{10}$$

In the 11-12-15 distribution, the same t_x value has a unit-normal z value given as:

$$z_1=\frac{t_x+\Delta}{\sigma_1} \tag{11}$$

where $\Delta = \mu_2 - \mu_1$ (i.e., slack in segment 11-12-15). Then, from (8) and Assumptions 1-5, 8, and 9, a control line for probability x, at event 11, will be offset horizontally from the original plan line by an amount t_x, where probability x is described as follows:

$$x=1.0-\left[\int_{-\infty}^{z_1} f(z)\,dz+\int_{-\infty}^{z_2} f(z)\,dz -\left(\int_{-\infty}^{z_1} f(z)\,dz\right)\left(\int_{-\infty}^{z_2} f(z)\,dz\right)\right]. \tag{12}$$

Given a control line probability x, (12) may be solved for z_1 and z_2, and these may be converted to a t_x using (10) or (11). In practice, however, the fastest route to a solution may come from trial and error calculations, starting with proposed t_x values and finding the associated xs. Using the above method at event 11, t_x for $x = 0.01$ is 1.75 weeks (as opposed to 3.97 weeks, when path segment 11-12-15 is *not* considered). Figure 8 shows the $p = 0.01$ control line through a progress plot section, located in this way, as well as the 0.01 control line that ignores path 11-12-15.

Note that the original plan line line now shows planned completion of event 12, a non-CP event, at 79.1 percent of the CP (where it would fall given an earliest possible start). Control line offsets t_x are calculated at events 12 and 14 just as shown above, except that the means and variances of both probability distributions are reduced appropriately (see the Appendix).

Discussion

Progress plots—like statistical process-control charts in the manufacturing setting—can be extremely powerful management tools only if we remember what they do and do not reveal. Progress plot and control chart put present performance immediately into historical context; they show, at a glance, whether managerial actions are succeeding or failing at keeping to the overall plan, and they show the cumulative effects of many small deviations from plan. They can warn that actual performance is deviating from planned performance while there is still time to make corrections; they "automatically" discriminate, statistically, between inconsequential variation from plan and problems that threaten a successful operation.

On the other hand, progress plots and statistical process control charts do not automatically expose the root cause behind deviations from plan. As indicated, the progress plot can imply certain reasons for project slippage (consistently underestimated task durations, or inadequate application of resources, for example), but it will not explain them. Nor will the progress plot predict problems that were unforeseen when the original project plans were made. The predictive power of the progress plot is limited to probability statements about on-time project completion—given that all of the original project planning assumptions still hold.

Appendix

Calculation of Offsets at Events 12 and 14, Fig. 8

Event 12 has a planned occurrence 8.8 weeks after event 11. At event 12, μ_1 of the 11–12–15 distribution is 6.2 weeks and the remaining σ_1 is now $\sqrt{1.250} = 1.118$. By event 12, task 11–14 has $9.2 - 8.8 = 0.4$ planned weeks remaining. μ_2 of this distribution is thus taken as $0.4 + 6.4 = 6.8$ weeks. And, by event 12, we assume that the remaining variance associated with task 11–14 is $(0.4/9.2) = 0.63$ of the original task variance. Thus, σ_2 is now taken as $\sqrt{0.63 + 1.467} = 1.448$. With these changes, (12) shows the control line offset t_x at event 12, for $x = 0.01$ to be 1.23 weeks.

At the planned occurrence of event 14, the remaining length of path 11–12–15 should be $8.8 + 6.2 - 9.2 = 5.8$ weeks. For t_x values at event 14, μ_1 is thus as 5.8 weeks. The variance of the remaining 11–12–15 path distribution is now (5.8/6.2) of the original task 12–15 variance (1.250), that is, 1.169, and σ_1 is thus $\sqrt{1.169} = 1.0812$. At event 14, the mean of the 14–15 distribution is of course 6.4 and σ_2 is $\sqrt{1.467} = 1.2112$. From these values and (12), t_x for $x = 0.01$ is 1.12 weeks at event 14.

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Evaluating Acquisitions In Consulting Engineering

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Abstract—**Many engineering managers are, for the most part, unaware of the strategic thinking and marketing-based planning dimensions surrounding the process of geographic diversification and acquisition decision-making. Yet, the acquisition and diversification planning process need not be complex. To explain how this can be accomplished, this paper first explores in considerable depth the strategic management planning process for acquisition decision making. The steps involved in the process of selecting and implementing an acquisition strategy for a consulting engineering organization will be devloped and discussed. This will be followed by a case study statistical evaluation of recent acquisitions within the consulting engineering services industry demonstrating the financial economic characteristics and computations. Finally, a work sheet will be presented for use in organizing and evaluating a set of distinct characteristics for comparing acquisition candidates.**

Manuscript recevied June 24, 1986; revised August 15, 1986.
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Introduction

Engineering managers are not as informed about the complexities of growth through acquisition and diversification as they are about managing highly specialized projects, where decision-making logic is dependent upon equipment-based technological solutions or even particular design product-oriented experiences. Virtually all growth acquisition decisions will require winning new markets and projects through cooperative team efforts involving combined marketing, technical and operating personnel, plus significant client involvement and acceptance [2]. The engineering acquisition experience must be viewed from a broader perspective than just motivation for immediate expansion of business revenues and profits. Growth through acquisition provides an opportunity to develop the company's technical capabilities and build a technological base with enhanced professional experience that can lead to future human resource and business growth.

Strategic Planning Process

Acquisitions by consulting engineering firms, while never considered low-risk ventures, are significantly more risky than most engineering managers anticipate. Perhaps this is why most of the published literature within the last ten years has employed a strong focus upon financial theory [3]. At least one-half the major acquisition consultants within the industry rely upon extensive quantitative techniques involving financial measures to analyze acquisitions [4]. Nevertheless, a new strategic approach is beginning to emerge which focuses upon not only financial attractiveness, but also extensive analysis of the market and human resource implications for the engineering firm's portfolio of skills [5].

Fig. 1, developed through cases study analysis described later in this article, illustrates the approaches to acquisition analysis in terms of time and effort focused upon the transaction. The left column shows the typical allocation of effort while the column on the right demonstrates the strategic significance that should properly be allocated to each function.

Five specific strategic planning considerations must be addressed if the acquisition and diversification efforts are to produce lasting value.

1) Will the acquisition strengthen competitive position, adding skills necessary to penetration and segmentation within a medium-attractive to high growth professional services market?

2) Will managerial philosophies and human resource values produce a compatible and synergistic reorganizational climate?

3) Will the proposed acquisition be legally and financially feasible, including enhancements to earnings, profitability, or taxation benefits?

4) Will the acquisition result in opportunities to develop the firm's technical capabilities, build a new technology and experiential base or contribute underutilized resources to sustain acquisition success and provide future business growth?

5) Will the acquisition contribute to the firm's risk management framework, lowering overall risk exposure, insurance premiums and justify investment returns per unit of risk?

While all firms develop strategic plans, explicitly or by default, systematic planning is more likely to improve profitability, reduce risks, and enhance commitment to organizational growth through acquisition.