A Course in

CRITICAL PATH PLANNING OF GRADUATE RESEARCH

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THE CRITICAL PATH method (CPM) has proven to be exceptionally beneficial over the last fifteen years for the control of project operations, and for task planning and control in many industries. In addition to its proven success in industry, the critical path method has been applied successfully in the education educational sphere for the planning of ChE curricula [1]. The vast majority of the literature on CPM concerns applications requiring computer solution of the critical path by parametric, linear programming [2], whereas non-computer methods are needed for the routine application of this method in small laboratory research projects. In this paper, a simplified procedure is presented for applying the critical path method to graduate research programs, using noncomputerized techniques readily available to the student. Recent experience with the method is drawn from several graduate-level ChE research programs.

TWO DIFFERENT FORMS

THE BASIC CONCEPTS of critical path planning were initially developed in two fundamentally different forms. The "probabilistic" approach was known as Program Evaluation of Research Tasks (PERT) or PERT with costs (PERTCO) [3]. In this form, individual research and development tasks, whose duration and cost could not be accurately estimated, were assigned a range of probable duration and cost. These data were then incorporated into a computerized critical-path control program. A second form of CPM, called Project Planning and Scheduling System (PPSS), was predicated on a more deterministic approach, where the controlling variables of individual tasks are assumed to be estimated with reasonable accuracy [4]. The latter approach has been utilized effectively in the chemical and construction industries [4, 5]. The deterministic approach is more suitable for graduate research planning provided that the controlling variables can be quantitatively assessed.

The critical path method is applied to graduate research programs . . . Experience shows a high correlation between task identification and effective task completion by the student.

TABLE I. Steps in the Critical Path Method

Phase I.	**Project decomposition into a realistic network of task sequences.**
	A. Assignment of individual tasks.
	B. Estimate of times and cost benefits.
	C. Construction of a precedence—contribution matrix.
	D. Assignments of topical sequences.
Phase II.	**Critical path determination for a normal project rate.**
	A. Construction of an arrow diagram.
	B. Determination of the critical path.
Phase III.	**Time-cost-benefit optimization**
	A. Estimation of times and cost-benefits for highest rate.
	B. Calculation of incremental cost slopes.
	C. Determination of the critical path.

NONCOMPUTER CPM

THERE ARE THREE important phases of the CPM method developed here for graduate research. These are summarized in Table I. In the first phase, the overall project is divided into distinct tasks. It is useful to divide long project operations into a sequence of separate tasks. The tasks are then ordered into topical sequences with the aid of a precedence-contribution matrix: each task follows its precedents, but should come before tasks to which it contributes. An arrow diagram is then constructed from which the critical path is determined, again using information in the precedence-contribution matrix. The program is finally optimized by calculating the incremental cost-benefits per unit of time saved, for alternative forms of the project tasks.

The noncomputer critical path method proposed for graduate research planning is perhaps best illustrated with an example. Consider a typical set of research tasks arising in a project having both analytical and experimental components. Following the steps listed in Table I, one first lists the individual tasks of the project and assigns values of the time required and the cost-benefit to each, as shown in the left-hand part of Table II. Dead times requiring no work input are separately listed. Next, a precedence-contribution matrix is constructed, as shown in Table III, where the precedent steps are identified, as are subsequent steps which benefit from each step. The information on precedents is then used to construct the topical sequences shown in Table III. Here, for example, task 2 is listed following task 1 in sequence because task 1 is a precedent, whereas task 3 is placed at the start of a new sequence because no precedent step is required. All duplicate tasks numbers in this table could be deleted to simplify the table.

The second phase of the method is the determination of the critical path for a normal project rate. For this, an arrow diagram is first constructed from the information in Tables III and IV, with arrows connecting each step to its required precedent steps, as shown by the solid lines in Fig. 1a. Then, Table II is examined to determine the first subsequent step to which a given step contributes. These contributions are denoted by the dotted lines in Fig. 1a.

It is evident from Fig. 1a that task 3 could preceed task 1, but there is no clear precedence requirement. It is appropriate, therefore, to further subdivide task 1 into two parts, where one part requires task 3 as a precedent. Note also, that several tasks are in parallel (i.e., 2, 4 and 6) and could be performed by a large work force. The graduate student constitutes a one-man crew, however, and therefore an addition criterion must be supplied to determine the task sequence. Two criteria are proposed here: (i) Table II is examined for each task in a parallel group (i.e., 2, 4 and 6). The number of contribution entries in the column for each is counted, and the task with the highest number of "C" entries is performed first. Alternately, (ii) the parallel tasks should be further subdivided and ordered so that the graduate student alternates his time between them, thereby gaining experience with all the tasks early in the program. Following criterion (i), one can readily arrive at the critical path program shown in Fig. 1b for the normal program rate. The critical path is denoted by double arrows, while idle time durations are denoted by wavey arrows (e.g., for task 2).

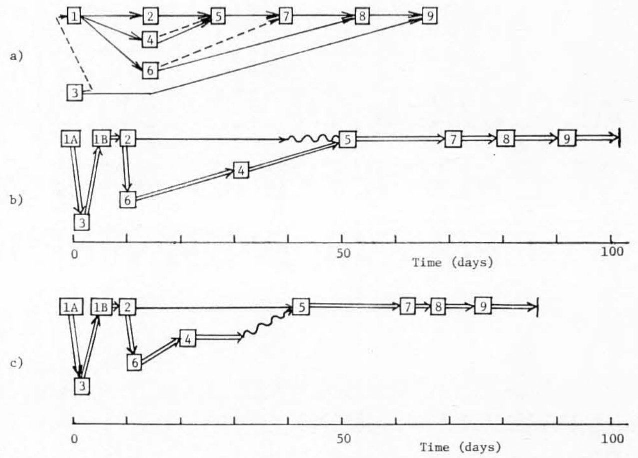

FIGURE 1. Task sequencing of a typical graduate research program: a) arrow diagram, b) critical path for a normal program rate, c) critical path for an accelerated rate.

(Continued on page 203.)

TABLE II. Time, Cost and Cost-Slope Estimates for a Typical Project

Task	Task Name	Normal Rate Time (d)	Normal Rate Cost-Benefit ($)	Accelerated Rate Time (d)	Accelerated Rate Cost-Benefit ($)	Incremental Cost Slope ($/d)
1	Define Problem	5	100	5	100	∞
2	Order Supplies	30*	520	30	520	∞
3	Lit. Survey	5	100	5	100	∞
4	Construct App.	20	1000	10	2000	100
5	Experimental	20	400	20	400	∞
6	Analyt. Calc.	20	700	10	1000	150
7	Data Reduction	10	200	5	200	0
8	Compare Theo & Exp.	10	200	10	200	∞
9	Write Reports	10	200	10	200	∞

*29 day dead time.

CPM METHOD: Donaghey

Continued from page 193.

The acceleration of any project step presupposes a subcontracting of project labor, often at the expense of graduate research experience. For example, the time required for construction of experimental apparatus can be shorted by purchasing ready-made apparatus, and data-reduction tasks could possibly be shortened by hiring an undergraduate assistant.

With accelerated project rates now accepted for tasks 4, 6 and 7, the resulting critical path becomes that shown in Fig. 1c. Here, the total project time is constrained by the duration of task 2 (i.e., waiting for ordered supplies to arrive) rather than by steps 6 and 4. Consequently, one of the two tasks need not be shortened.

TABLE III. Precedence-Contribution Matrix

Tasks Affected	1	2	3	4	5	6	7	8	9
1		P	C	P		P			P
2					P				
3									
4		C			P				
5	C	C		C			P		
6	C		C					P	
7			C			C		P	
8						C			P
9			C		C	C	C	C	

P = Precedence **C = Contribution**

Table I shows that task 6 has the higher cost slope, and, therefore, this task should be carried out at the normal rate.

RECENT RESULTS

THE CRITICAL PATH method outlined above has been tested in a number of graduate research programs in solid-state electrochemistry, process kinetics and transport phenomena during the past few years. Experience has shown that the initial critical path plan must be revised periodically during the program to take advantages of new discoveries or to avoid limiting difficulties. Experience has also shown a high correlation between task identification and effective task completion by the student. It has also been found that long-term segments of the total program should be subdivided so that the student gains familiarity with all type of program tasks in operation terms early in the program.

TABLE IV. Assignment of Topical Sequences

	Step Number					
Sequence	1	2	3	4	5	6
A	1	2	5	7	8	9
B	3					
C		4	5	7	8	9
D		6				

CONCLUSIONS

THE FORM OF THE critical path method presented here differs from earlier forms is having these important characteristics: (1) the educational experience derived from interacting research tasks is counted as a cost benefit, (2) the critical path is constructed with a minimum of subcontracted or simultaneous tasks, and (3) the method presented does not require a computer to apply it. □

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