Seventh Edition

CPM in Construction Management

- Apply the critical path method (CPM) to construction projects
- Save time, cut costs, and reduce claims
- Learn CPM network techniques from a detailed case study

JAMES J. O'BRIEN

FREDRIC L. PLOTNICK

CPM SOFTWARE ON CD-ROM

CPM in Construction Management

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Preface

The original purpose of this book, in 1965, was to present and discuss the Critical Path Method (CPM) and its use in the construction industry. At that time, CPM was a young but proven technique—usually considered to be optional. When the 2nd edition was published in 1971, the network approach to scheduling was becoming a regular requirement in construction contracts. The 3rd edition, published after 25 years of experience in the application of CPM, described highlights of that experience and its significance to the practical use of CPM.

The basic strength of CPM continues to be its ability to represent logical planning factors in network form. One reviewer noted: "Perhaps the most ironic aspect of the critical path method is that after you understand it, it is self-evident. Just as an algebra student can apply the rules without full appreciation of the power of the mathematical concepts, so can the individual apply CPM or its equivalent without fully appreciating the applicability of the method."

The book first describes the development of CPM and its practical use in the construction industry. The basic technique is described in sufficient depth for the reader to apply it to practical construction situations. The John Doe case study is used throughout the book to describe basic CPM network techniques and then to illustrate such special functions as updating, cost control, resource planning, and delay evaluation. Optimum methods of specifying the use of CPM are described in sufficient detail to be incorporated directly into construction specifications.

Since the 2nd edition, CPM has become widely utilized as an analytical tool in the evaluation, negotiation, resolution, and/or litigation of construction claims. This aspect is thoroughly explored in the current edition. Legal precedents for the use of CPM during litigation are provided.

In the 1980s, computer calculation shifted from mainframe programs to personal computers (PCs). PCs were the wave of the past two decades. The ubiquity in the 2000s of the internet and the wave of additional interconnectivity linking individual PCs now has the appearance of coming full circle and bringing back to CPM many of the strengths and weaknesses of the era of the mainframe. However, the approaches and procedures suggested in the first six editions are, almost without exception, still valid.

Network techniques are basic and logical, but assimilation of the network concept does take time. Further, an effort is required to build an experience level, which in turn builds confidence. This book aims to be a useful element in the development of that conceptual experience and confidence on the part of new users of CPM techniques.

James J. O'Brien, P.E., PMP

I was introduced to the concepts of CPM as a student in college for 2 weeks in a course covering many aspects of construction management. It was a revelation and led to additional independent study, including a grant of computer time (on the giant mainframe) from Drexel University's Computer Center (Philadelphia, PA), on which my first CPM software program was written. It was at this time that I realized the potential value of CPM to resolve disputes involving delay that planted the seed for my future legal education.

Several years past, during which I worked for several construction and consulting firms, and a stint as assistant corporate counsel for a large firm involved in international construction. In 1983, I formed EnProMaC (Engineering & Property Management Consultants, Inc.). Interestingly, in 1983 Joel Koppelman and Dick Faris formed Primavera Systems. One of my first efforts was to rewrite my CPM software program to run on my Osbourne I (a pre-IBM PC with 64KB of RAM and 90KB of floppy disk storage) running as a routine under dBASE II (a database program by Ashton Tate). At that time, I never dreamed that a market might exist for such software—assuming such could be rewritten for user-friendliness.

The success that Messrs. Koppelman and Faris achieved in launching Primavera is largely based upon their attention to making their software user-friendly—and in giving their customers that which is asked for. CPM theory has a number of limitations, as does any system that attempts to model reality. Bending the rules of CPM analysis can, in some instances, circumvent these limitations. In many cases special features have been added to Primavera, which have legitimate uses in very limited situations, but which should be used with extreme care. The many competitors of Primavera also have added features that extend and modify the basic concepts of CPM—each in their own fashion—and each that differ subtly from each other. One of my contributions, upon being added as a co-author to the 5th edition, was to address these special features and their proper use.

In 1982, Drexel University asked me to create a course on CPM. This was a major factor in deciding to form my own consulting firm, so as to have more control over my time to pursue research and teaching. Over the years, I have had the opportunity to teach—and that is to share discussion with my students on—CPM, as well as courses on contracts and specifications, engineering law, and project administration. Considering the means of best teaching CPM led to many of the organizational changes of the 6th edition. In 2003, *ENR* featured Jim O'Brien and me in an article "Off the Critical Path" on issues relating to the legitimacy of CPM analyses. This too forced me to take time to think and to push the envelope.

The result was RDM, or Relationship Diagramming Method, outlined as an academic idea in the 6th edition. Much to my satisfaction, this idea has been well received. After converting my notes and comments of this text to the form of a dissertation, Drexel University conferred upon me the Ph.D. degree. And Primavera embraced the concept by requesting that I assist their implementation of RDM functionality to their line of software, starting with their high-end Pertmaster Risk Analysis product.

I, in turn, have been happy to provide my RDCPM® certification of proper implementation to Pertmaster. And thus many of the additions to this 7th edition relate to the evolving standard for Relationship Driven CPM. Other additions relate to how other entities and organizations have similarly responded to the call for greater transparency raised in that 2003 article. The continuing evolution of software, from both the viewpoint of computer code and the consolidation of vendors to enterprise software providers (Welcom to Deltek, Primavera to Oracle), is also addressed.

It continues to be my hope that my contributions to this 7th edition will bring the confluence of the basic theory of mathematics, the applied discipline of engineering, and the framework for collaboration by adversarial parties provided by the study of law, all to assist the practitioner of planning and scheduling.

Fredric L. Plotnick, Ph.D., Esq., P.E.

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Jim and Fred dedicate this 7th edition to the memories of:

James E. Kelley Jr., April 30, 2008

John W. Fondahl, September 13, 2008

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CPM in Construction Management

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Part

1

Introduction to CPM Planning and Scheduling

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Chapter

1

Introduction to CPM Planning and Scheduling

This introduction discusses some factors that make the case for why planning and scheduling is best performed by the Critical Path Method (CPM). It covers some of the history behind its development and relays some thoughts on where the process may be going in the future. The interplay between the theory of mathematics that underlies the methodology and the modifications needed to make the methodology more practical are themes that continue throughout the text. It is hoped that the conclusion drawn by the reader will be that it is the Scheduler who must balance these two ideals, mathematics and engineering, to provide a useful and user-friendly tool to the users of CPM in construction management, manufacturing, software design and other users in the world of projects that must be finished on time and within budget.

1.1 Scheduling Is for Everyone

Scheduling is a discipline that is performed by every person, every day. Should you first shave or brush your teeth in the morning? If you are scheduling for one person only, the process is rather simple. You can prepare a "ToDo" list and then choose in what order the items on it are to be performed. However, the choice of what to do first is not completely random. Perhaps there are physical restrictions, such as "shower before dressing" or "cook breakfast before eating." Perhaps there are logistical restrictions, such as combining one trip to buy milk, pick up the dry cleaning, and refuel your car, rather than making three trips to accomplish these three items on your "ToDo" list. Perhaps the order of performance is pure personal choice, such as put on right shoe before left shoe.

Even at this simple level, not all is what it seems to be. If you are in a hurry, you might begin eating a portion of your breakfast while still cooking the rest. If your dry cleaner is open only from 10:00 AM to 6:00 PM and if your car is very low on gas, you may have to refuel on your way to work, pick up your dry cleaning at lunch, and buy milk on the way home from work. If you have a foot or leg injury, you may need to put on your left shoe first.

If you want to schedule the tasks of two or more persons or the work flow of two or more machines (even if both are under the supervision of one person), the process becomes much more complex.

1.2 We Teach Carpentry—Not "How to Use Your New Power Saw"

If the process of scheduling were a simple matter, requiring merely rote actions without the need for thought, perhaps good schedules could be created by a software Wizard. After clicking your way through a preset series of screens, you would have your schedule. Perhaps then, the request of an old client for a device where building blueprints are fed in one end and a schedule is printed out the other end would be feasible. Alas, it is not so–scheduling is a complex process and the mathematical underpinning is at the level of rocket science.

Scheduling is an application of special knowledge or judgment of the mathematical, physical, or engineering sciences to the conception or implementation of creative work. Scheduling, formally or informally, good or bad, is practiced in the planning, progress, and completion of designs, analyses, or implementation performed in connection with utilities, structures, buildings, machines, equipment, processes, systems, works, projects, and industrial or consumer products or equipment of a mechanical, electrical, electronic, chemical, hydraulic, pneumatic, geotechnical, or thermal nature. The wording of the preceding sentence is taken from the statute defining Engineering for a reason: scheduling is a branch of engineering.

Implicit in the teaching of engineering, or of the supporting fields of science and mathematics, is the need to understand the process and not merely trust the black box. It is important to understand the mathematical underpinning of modern CPM software rather than to merely begin clicking away. Children are still taught how to add and how to spell even though they have access to calculators and computer word processing software aided with spell-check. One reason is that even the best spell-check software can leave errors uncaught. Another reason is to understand what the numbers on calculators mean. Many of us may remember a freshman physics class where we were taught that 2.5×3.01 is not equal to 7.525, but rather to 7.5, since the result will never be more accurate than the least accurate input (for those who have not taken freshman physics, $2.50 \times 3.01 = 7.53$ and $2.500 \times 3.010 = 7.525$).

Even the terminology can be misleading. CPM was once noted as a tool in the process of ***Planning and Scheduling***. First we must plan, then we can use the computer to perform the rote calculations (that we understand and could perform given time) to generate the schedule, and then we must read the output with a knowledge of the assumptions and tolerances involved. Today, however, we can purchase software that includes a Wizard to simplify or ignore the need for planning, perform the calculations while allowing user overrides to generate the "correct" or "desired" result, and provide killer report and graphics applications to display the schedule results.

It is the purpose of this text to teach carpentry and not merely the features and benefits or, "how to use" your new power saw. It is the purpose of this text to teach the process of planning and scheduling by means of the Critical Path Method of Analysis. We can best start by reviewing how this field of mathematics and engineering was developed.

1.3 History of Scheduling Systems

CPM was developed specifically for the planning of construction. The choice was fortuitous, since construction accounts for more than 10 percent of the annual gross national product. Almost every activity and every person is affected to some degree by new construction or the need for it. Most projects are started well after the need has been established, seeming to follow the whimsy, "If I'd wanted it tomorrow, I'd have asked for it tomorrow."

The construction industry is a heterogeneous mix of companies ranging in size from the large operations to one-person operations. No matter the size, construction companies face similar situations and, to some degree, similar pressures. Many factors, such as weather, unions, accidents, capital demands, and work loads, are either beyond individual control or difficult to control. New problems in project approvals due to increased public awareness include pollution and ecological controls. CPM does not offer clairvoyance, but it does assemble all the information to the project managing team.

Initially, CPM spotlighted construction and the contractor. The owner, architect, engineer, and public agencies involved in a project are like the backer, producer, and director of a Broadway show. Without them, the show cannot go on, and any lack of competence, motivation, or interest on the part of any one of the team members can delay a project. However, the contractor is the performer who ultimately makes or breaks the construction show.

The typical contractor is a planner who generally uses instinctive methods rather than formal scheduling. Prior to 1957, contractors had little choice than to operate this way because no comprehensive, disciplined procedures for planning and scheduling construction projects existed. And prior to the mid 1980s, contractors desiring to utilize the benefits of the newer methods had to rely on outside consultants, who in turn had to rely on computer service bureaus and their large mainframe computers.

One of the keys to the success of CPM is that it utilizes the planner's knowledge, experience, and instincts in a logical way first to plan and then to schedule. CPM can save time through better planning, and in construction, time is money.

The Egyptians and Romans worked construction miracles in their day, and surviving ruins attest to the brilliance of their architecture, but little is known of their construction planning and scheduling. Other historical project managers include Noah, Solomon, and the unknown architect who designed the tower of Babel. Again, history records much about the construction details but little about the methods of control.

1.4 The Ordered "ToDo" List

Many of us make lists of things to do (i.e., a "ToDo" list). Those who are well organized may make the list in a logical order–for example, a shopping list based upon the layout of a store or supermarket. Perhaps a fanatic to organization may first make a list of activities (or, from our example, items to be purchased) and then copy it a second time to the preferred order that it is to be performed. The use of word processing or organizing software adds a modern wrinkle to this age-old method of planning and scheduling. However, there are no rules widely published to guide the development of "ToDo" lists.

1.5 Gantt Charts and Bar Charts

In the mid-nineteenth century, at least one writer discussed a work versus time graphical representation very similar to today's bar charts, but it remained for Henry L. Gantt and Frederick W. Taylor to popularize their graphical representations of work versus time in the early l910s. Their Gantt charts were the basis for today's bar graphs, or bar charts.

Taylor and Gantt's work was the first scientific consideration of work scheduling. Although their work was originally aimed at production scheduling, it was readily accepted for planning and recording the progress of construction. Today, the bar graph remains an excellent graphical representation of activity because it is easy to read and understood by all levels of management and supervision.

If the bar graph is so well suited to construction activity, why look for another planning aid? Because the bar graph is limited in what information it can retain. In preparing a bar chart, the Scheduler is influenced almost necessarily by the desired completion dates, often working backward from the completion dates. The resultant mixture of planning and scheduling is unfortunately no better than wishful thinking.

When a bar graph is carefully prepared, the Scheduler goes through the same thinking process as the CPM planner. However, the bar graph cannot show (or record) the interrelations and interdependencies that control the progress of the project. And, at a later date, even the originator is often hard pressed to explain the plan by using the bar graph.

Figure 1.5.1 is a simplified bar chart of the construction of a one-story office building. Suppose, after this 10-month schedule has been prepared, the owner asks for a 6-month schedule. By using the same time for each activity, the bar chart can be changed as shown in Figure 1.5.2. Although the chart looks fine, it is not based on logical planning; it is merely a juggling of the original bar graph.

The general contractor usually prepares the overall construction plan, which is sensible because the schedules of the other major contractors depend on the general contractor's schedule. Note that in Figures 1.5.1 and 1.5.2, the general contractor's work is broken down in some detail, with both the mechanical and electrical work shown as continuous lines that start early and end late. In conformance with the bar graph "schedule," the general contractor will then often push the subcontractors to staff the project as early as possible with as many mechanics as possible. Conversely, the subcontractors want to come on the project as late as possible with as few mechanics as possible. The result is that the general

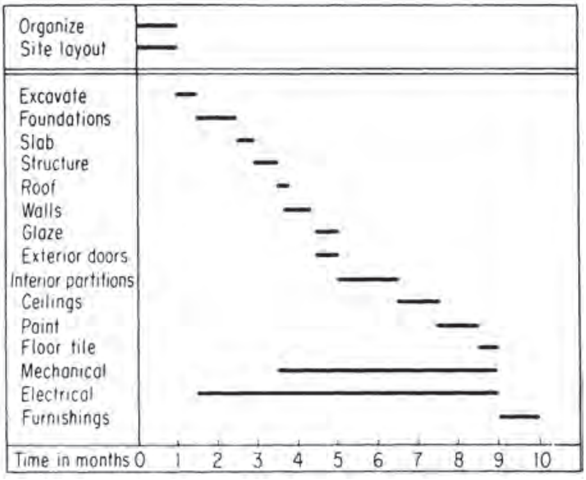

Figure 1.5.1 Bar chart for a one-story building.

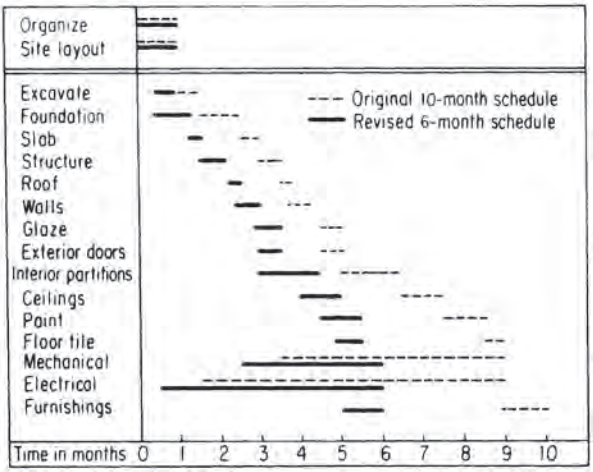

Figure 1.5.2 Revised bar chart for a one-story building.

contractor will often complain that the subcontractors are delaying the project through lack of interest. At the same time, the subcontractors will often complain that the general contractor is not turning work areas over to them, forcing them to pull out all the stops to save the schedule.

As in most things, the truth lies somewhere between the extremes. CPM offers the means to resolve these differences with specific information rather than generalities. The bar chart often suffers from a morning glory complex: It blooms early in the project but is nowhere to be found later on. We can suppose some general reasons for this disappearing act. Prior to the construction phase, the architect, the engineer, the owner, or all three are trying to visualize the project schedule in order to set realistic completion dates. Most contracts will require the submission of a schedule in bar graph form soon after a contract is awarded. Once the project begins to take shape, however, this early bar chart becomes as useful as last year's calendar because it does not lend itself to planning revisions.

Although progress can be plotted directly on the schedule bar chart, the S curve has become popular for measuring progress. The usual S curve consists of two plots (Figure 1.5.3); the scheduled dollar expenditures versus time and actual expenditures versus time. Similar S curves can be prepared for labor hours, equipment and material acquisitions, concrete yardage, and so on. Though this presentation can be interesting, it does not provide a true indication of project completion. For instance, a low-value critical activity could delay the project completion far out of proportion to its value.

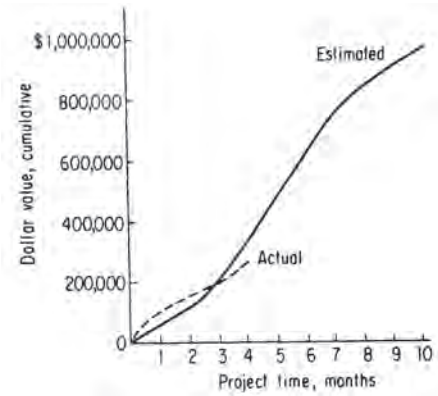

Figure 1.5.3 Typical S curve.

Misuse of bar charts does not prove that they should be discarded. To throw out bar charts is like throwing out the baby with the bathwater.

1.6 Development of the Critical Path Method of Scheduling

In 1956, the E. I. DuPont de Nemours Company set up a group at its Newark, Delaware, facility to study the possible application of new management techniques to the company's engineering functions.[1] The planning and scheduling of construction projects was one of the first areas studied. The group had a UNIVAC I computer (the third unit built) at its disposal, and they decided to evaluate the potential of computers in scheduling construction work. Mathematicians worked out a general approach; they theorized that if the computer was fed information on the sequence of work and the length of each activity, it could generate a schedule of work.[2]

In early 1957, the Univac Applications Research Center, under the direction of Dr. John W. Mauchly, joined the effort with James E. Kelley, Jr., of Remington Rand (UNIVAC) and Morgan Walker of DuPont in direct charge at Newark, Delaware. The original conceptual work was

[1]Hayward and Robinson, *Preliminary Analysis of the Construction Scheduling Problem*, internal paper, Engineering Department, DuPont Company, December 1956.

[2]James E. Kelley and Morgan R. Walker, "Critical Path Planning and Scheduling," *Proceedings of the Eastern Joint Computer Conference*, pp. 160–173, December 1–3, 1959; see also James E. Kelley, "Critical-Path Planning and Scheduling: Mathematical Basis," *Operations Research*, vol. 9, no. 3, pp. 296–320, 1961.

revised, and the resulting routines became the basic CPM. It is interesting that no fundamental changes in this first work have been made.[3]

In December 1957, a test group was set up to apply the new technique (then called the Kelley-Walker methods). The test team (made up of six engineers, two area engineers, a process engineer, and an estimator) and a normal scheduling group was assigned to plan the construction of a $10 million chemical plant in Louisville, Kentucky.

As a control, the new scheduling team worked independently of the normal scheduling group. This is the only documented case of a comprehensive comparative CPM application. The test group had not been part of the development of the CPM method, but members were given a 40-hour course on the technique before starting the test.

The network diagram for the project was restricted to include only the construction steps. The project was analyzed beginning with the completion of its preliminary design. The entire project was subdivided into major areas of scope, and each of the areas was analyzed and broken down into the individual work activities. These activities were diagrammed into a network of more than 800 activities, 400 of which represented construction activities and 150 design or material deliveries.

The ability of the first team was such that a larger-capacity computer program had to be developed for support. By March 1958, the first part of the network scheduling was complete. At that time, a change in corporate outlook, plus certain design changes, caused a 40 percent change in the plan of the project. Both planning groups were authorized to modify the plan and recompute schedules. The revisions, which took place during April 1958, required only about 10 percent of the original effort by the CPM test team, substantially better than the normal scheduling group.

One significant factor involved the determination of critical delivery items. The normal scheduling group arbitrarily assigned critical categories, while the CPM group determined critical activities from its network analysis. From the analysis, it was determined that only seven items were critical, and three of these were not included in the normal scheduling group's list.

The initial test scheduling was considered successful in all respects. In July 1958, a second project, valued at $20 million, was selected for test scheduling. It also was successfully scheduled. Since the first two projects were of such duration that the complete validity of the system could not be established, a shorter project, also at DuPont in Louisville, was selected for scheduling.

The third project was a shutdown and overhaul operation involving neoprene, and one of the materials in the process was self-detonating, so little or no maintenance was possible during downtime. Although

[3]James E. Kelley, "Computers and Operations Research in Road Building," *Operations Research, Computers and Management Decisions*, Symposium Proceedings, Case Institute of Technology, January 31–February 1 and 2, 1957.

the particular maintenance effort had been done many times, it was considered to be a difficult test of the CPM approach.

In the first CPM plan, the average shutdown time for the turnaround was cut from 125 to 93 hours, and in later CPM applications, it was further cut to 78 hours. The resultant time reduction of almost 40 percent far exceeded any expectations.[4]

1.7 Development of the PERT Method of Scheduling

The development of CPM was enhanced when the U.S. Navy Polaris program became interested in it. The Polaris program staff had developed its own network system known as Performance Evaluation and Review Technique (PERT). The DuPont work is considered antecedent material for the development of PERT.

The Polaris fleet ballistic missile (FBM) system was initiated in early 1957. To manage the program, a Special Projects Office (SPO) was established under the direction of Admiral Raborn. The Office is generally credited with having developed the PERT system.

One of the key people involved in the development of PERT was Willard Fazar, who noted that the various management tools available for managing the Polaris program did not provide certain information essential to effective program evaluation. In particular, they did not furnish the following:

1. Appraisal of the validity of existing plans in terms of meeting program objectives
2. Measurement of progress achieved against program objectives
3. Measurement of potential for meeting program objectives

The search for a better management system continued throughout the fall of 1957. At that time, the Navy was cognizant of the development of CPM at DuPont. In January 1958, the SPO initiated a special study to determine whether computers could be used in planning and controlling the Polaris program, and on January 27, 1958, the SPO directed a group to undertake the task of formulating the PERT technique.[5]

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[4]Hayward and Robinson, "Preliminary Analysis of the Construction Scheduling Problem," Engineering Department, DuPont Company, December 1956.

[5]D. G. Malcolm et al., "A Network Flow Computation for Project Cost Curves," Rand Paper P-1947, Rand Corporation, March 1960; D. G. Malcolm, J. H. Roseboom, C. E. Clark, and W. Fazar, "Applications of a Technique for Research and Development Program Evaluation," *Operations Research*, vol. 7, no. 5, pp. 646–699, 1959; and W. Fazar, "The Origin of PERT," *The Controller,* vol. 30, p. 598 ff., December 1962.

The goal of the group was to determine whether improved planning and evaluating research and development work methods could be devised to apply to the Polaris program, which involved 250 prime contractors and more than 9000 subcontractors.

The PERT program evolved, and included the development of detailed procedures and mechanics phases, which were reported in formal documents. The PERT method, as described in the phase II report, was designed to provide the following (in addition to the three on the previous page):

1. Increased orderliness and consistency in planning and evaluating
2. An automatic mechanism for identifying potential trouble spots
3. Operational flexibility for a program by allowing for a simulation of schedules
4. Rapid handling and analysis of integrated data to permit expeditious corrections

The PERT system, programmed at the Naval Ordinance Research Calculator, was implemented in the propulsion component, which was followed by an extension to the flight control and ballistic shell components, and finally, to the reentry body and guidance component.

About a year after the start of the PERT research, the system was operational. This was outstanding considering the typical 36 percent time overrun for developing other weapons systems.

Following its success in the Polaris program, PERT was incorporated voluntarily in many aerospace proposals in 1960 and 1961. In some proposals, PERT was added principally as window dressing to make the proposal more attractive to the government. But thanks to its basic soundness and the acumen of the engineering staff members involved, PERT often stayed on as a useful planning tool even though it had entered some companies through the backdoor.

1.8 Comparison of CPM and PERT

The key difference between CPM and PERT is that one identifies activities of finite and reasonably estimated duration while the other identifies events of zero duration separated by “some form of activity” only loosely understood to be performed within a range of possible durations. This range of durations varies from an optimistic estimate (or shortest time until the next event will occur) to a “most likely” estimate to a pessimistic estimate. This dichotomy was understandable since the duration of an activity, relating to a known quantity of work, was fairly capable of estimation; the duration between events, based upon a scope only vaguely understood, was much more a “guestimate.”

The theory behind the PERT method was based upon the interplay between these estimates of duration and the statistical likelihood of a project outcome as the actual duration experienced may fluctuate among the three. However, the early computers of the 1950s and even the 1960s did not have the necessary speed or memory to fully utilize the theory and the three estimates were usually combined into one (often by separate calculation by hand alongside the computer) using the formula

$$\text{DUR} = \frac{(O + 4M + P)}{6}$$

where O = Optimistic
M = Most Likely
P = Pessimistic

The important distinction to remember, before considering the newer offshoots of CPM, is that CPM measures performance of defined activities and the durations of defined activities, while PERT measures the reaching of defined events and the passage of time between these events. Another important difference is that CPM durations are of defined events, while PERT durations are of undefined activity between events.