PLANNING AND SCHEDULING SOFTWARE PROGRAMS WITH PERT

BY

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ABSTRACT

The use of the Program Evaluation and Review Technique (PERT) in planning and scheduling software programs was discussed in this thesis. A real world program, referred to as the Wrap-Around Simulation or WAS Project, was selected to illustrate that complex efforts in the software domain can respond favorably to modern planning and scheduling techniques.

The WAS Project included the provision of a digital simulation of the shipboard environment in which a Digital Fire Control Computer (DFCC) would operate as part of a Digital Fire Control System. The digital simulation afforded a well controlled and conclusive checkout of the operational program contained in the DFCC and as such precluded the necessity of installing the DFCC aboard ship to evaluate its performance.

Basic PERT theory was presented and the mechanics of network generation were developed. The WAS Project was planned and scheduled in detailed step-by-step fashion as dictated by the philosophy and techniques discussed.

The analysis indicated that PERT can be an effective if not necessary tool for the manager of software as well as hardware projects. It was recommended that the greatest emphasis be placed on the activity time estimate.

The accuracy of the entire PERT approach is completely dependent on the validity of the time estimates. If time and funding permit, an analysis of variance of activity durations was strongly recommended to determine the feasibility of possible alternate plans.

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PREFACE

This thesis originated as an attempt to improve the apparent inefficient methods of planning and scheduling software programs. Although modern management engineering techniques are widely used in planning hardware efforts, projects in the software and R & D areas sadly lack such treatment.

It is the purpose of this thesis to demonstrate the applicability of a proven, effective managerial tool, the Program Evaluation and Review Technique, to the relatively untouched software domain.

Included in this paper are an introduction to the PERT/TIME method, its basic rules and regulations, and an application to a real-world software program. The PERT/COST technique, an outgrowth of the PERT/TIME concept, is not discussed.

The Author's thanks go to Prof. Joseph Rich of the Management Engineering Department of Newark College of Engineering for his technical guidance and advice. Thanks are also extended to Messrs. John Fare and Jack Morris of the Sperry Gyroscope Company for the information and data pertaining to the software project discussed in the thesis. Their generous cooperation throughout the writing of this paper was invaluable. Lastly, the author is indebted to Mr. James I. Anderson of the Sperry Gyroscope Company who acted as a most helpful and critical grammarian and rhetorician.

H. M.
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CHAPTER I : INTRODUCTION

IMPORTANCE OF PLANNING AND SCHEDULING

"The study of the managerial and administrative phases of business is so new that as yet there has not emerged a standardized terminology that is generally accepted."[1] That this statement appears in a textbook frequently utilized in today's engineering schools enforces the author of any paper on a management topic to make clear his concept of management, at the very outset.

The science of management embraces four major functions:

- Selection of the objectives of the enterprise or project.
- Determination of the requisites to meet the objectives.
- Allocation of available resources to achieve the objectives according to a plan and schedule.
- Control of the entire process from commitment to completion.[2]

The success with which a particular management meets these tasks can be measured by comparison of planned vs.

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1. Spriegel, W. and Lansburgh, R., Industrial Management, John Wiley and Sons, Inc., New York, 1955, p. 1.8.

2. Martino, R. L., Project Management and Control, Volume I, Finding the Critical Path, American Management Association, New York, 1964, p.16.

actual cost and time figures and further, by the response of its managers and methods when plans go awry. The lack of success that many companies are presently experiencing indicates that management is a tough business indeed. The margins for error between profit and loss or success and failure have shrunk. Rapid technological advances, much keener competition (to the point of cutthroat, in the missile and space industries), and shorter product life-spans have merged to make management a tougher, more demanding effort. Today's managers must make the most effective decisions based on considerations of alternates and their respective costs, risks inherent in each, and the consequences if decisions must be delayed. Any failure here can be catastrophic. The undesirable extra costs of idle time of either manpower or equipment must be minimized. Unless a company has methods of developing effective plans for a project, can allocate its resources to the project economically, and can maintain rigid control of all aspects of the program throughout its life, that company will not exist for long in today's world.[3]

"Efficient planning...always means the difference between 'on-time' and 'late' and it can mean the difference between success and failure."[4] Vital then, to

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3. Martino, op.cit., pp. 13-14.

4. Ibid. p. 16.

effective management are the functions of planning and scheduling.

Planning During the Acquisition Phase

Under the present system of contract-awarding by military agencies, many companies of the missile and space industry rise or fall on their technical proposals. The ability of a company to plan, organize, and carry out a project is reflected in no small way by its submitted proposal. Indeed, the over-all plan for the program may be more important than the technical approach and could prove to be the decisive factor. If the proposal includes a definitive program management and reporting plan, a clear cut organization including subcontractors, and a feasible schedule highlighting major project events and milestones, the bidding company will assume a competitive stature in this highly competitive of markets.[5]

Planning is, therefore, as important during the acquisition phases of a project as it is once the job is officially "in the house."

Basic Concepts Defined

Once the importance of the planning and scheduling

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5. Aalseth, J. E., "Hints for Reliability Engineers on Technical Proposals", Evaluation Engineering, Vol. 3, no. 5, August, 1964, p.41.

functions is recognized, an explicit definition of each should be firmly established and realized by all the managers of a company and, if possible, all the employees.

Basically, planning is choosing among alternatives. Specifically it is the decision-making function wherein the company objectives are selected and the methods of achieving them are decided upon. The establishment of the policies and procedures of a company is part of the planning function.[6]

Scheduling is the managerial control function whereby the precise use of available resources is regulated with respect to time. Typical of areas of consideration here are availability of resources, due dates, and sequences of operation. Decision-making in these areas is part of the scheduling process.[7]

The important sub-function of scheduling, dispatching, is deserving of separate and final mention. Dispatching affords the detailed information on sequencing of operations. "It provides answers to the question,

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6. Kast, F.E. and Rosenzweig, J.E., "Science, Technology, and Management: an Overview", Science, Technology, and Management, McGraw-Hill Book Company, Inc., 1963, p. 27.

7. Math, J.F. and Thompson, G.L., "Introduction", Industrial Scheduling, Prentice-Hall, Inc., 1963, p.IX.

'What should be done next?' asked whenever a man or machine has completed a task."[8] Although it is often considered to be a duty of the scheduling function, dispatching is still important enough to merit in-depth, systematic study.

The degree to which a company is successful in the performance of any of these functions is dependent upon the performance of the other two. Good planning and poor scheduling are mutually exclusive; a recognition of this brings home the great necessity for major efforts in these decision-making functions of management.

PLANNING AND SCHEDULING LARGE ENGINEERING PROJECTS

On November 19, 1964, Defense Secretary McNamara announced the intended closing of 95 military installations involving the potential displacement of over 63,000 jobs. The operations of these bases will be terminated "...in an economy move by the Administration."[9]

On November 12, 1964, Charles W. Perelle resigned his post as President of the American Bosch Arma Corpora-

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8. Conway, R.W. and Maxwell, W.L., "Network Scheduling by the Shortest-Operation Discipline", Industrial Scheduling, Prentice-Hall, Inc., 1963, p.277.

9. Raymond, Jack, "63,000 Will Lose Jobs at 80 Bases in U. S.", N. Y. Times, Nov. 20, 1964, p.l.

tion, a company which has seen two major government contracts cancelled during the last two years. Those contract losses have forced the company to layoff over 75% of its labor force and now the company is facing possible dissolution. Perelle, in discussing the situation in his resignation speech, said, "There is no reason to be sore if you've lost the competition but when you win it and you've been dealing with the service all your life and the rules are changed, it's hard to swallow."[10]

Heavy lay-offs numbering in the thousands, sweeping and abrupt changes in corporate-level management personnel, and publicized low earnings reports of several well-known large corporations have recently become regular enough that Americans in all walks of life are either affected by them or know someone who is. The rules-change referred to by Perelle and the closing of the Brooklyn Navy Yard, both perpetrated for reasons of economy, have made all New Yorkers aware of the cost-conscious approach of the present administration. Indeed, Americans in other sections of the country have become cognizant of our government's thinking through similar experiences. The questions most people are now asking are "Why have costs run so high at these bases?" and "What can be done to avoid such shutdowns in the future?"

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10. Caro, Robert A., Long Island Newsday, Nov. 13, 1964, p.12.

The Trend of the '50's

What is apparent to all citizens today was recognized in the late 1950's by market and trend analysts. In 1962, a book entitled "The Weapons Acquisition Process: An Economic Analysis" was published by the Harvard Press. This work presented the results of a three year research program in which the development cost and time variance factors for 12 large weapons programs and several multi-million dollar commercial projects were analyzed. The results for the 12 military programs indicated an average time factor increase of 1.36 and an average cost factor increase of 3.2. The commercial projects, all of which included extensive developmental effort, showed average time and cost increment factors of 1.4 and 1.7 respectively.[11]

In 1963 the Director of Defense Research and Engineering, Dr. Harold Brown, appeared before the Congressional Sub-Committee on Military Appropriations and presented a list of 57 defense programs which had been cancelled during the period 1953 to 1963. These projects had absorbed a total expenditure of 6.2 billion dollars.[12]

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11. Miller, Robert W., Schedule, Cost, and Profit Control with PERT, McGraw-Hill Book Co., Inc., New York, 1963, pp.10-11.

12. Miller, Op.Cit., p.13.

The testimony of Dr. Brown along with the studies of the Harvard Business School only authenticated what had been common knowledge to government and industry personnel engaged in large technical projects. Cost increases of over 100% and due date slippage of months and even years have not been uncommon in many of our missile and space projects. The problem became critical in the mid '50's when the number and cost of government defense programs suddenly increased. By the early '60's the situation was completely out of hand, partially due to the panic created by the surprise Sputnik achievement but in large part because of the increased size and complexity of the space and weapons programs themselves. At this time some of our government officials in high decision-making positions felt ahead of the game if a project were completed at 2 to 3 times the original estimated cost.[13]

The Government Becomes Cost-Conscious

But then the work of Dr. Brown and the Harvard Business School supported by similar studies by the RAND Corporation began to impress the highest ranking government officials in the country. It is no secret that former President Kennedy directed Secretary of Defense McNamara to take a long, hard look at the situation with

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13. Miller, R.W., Op.Cit., p.12.

the ultimate objective to alleviate it via corrective action. And President Johnson has only seemed to intensify the Kennedy approach. One of his first official measures when he took office was to cut the defense budget and tighten the defense industry's belt. He sent a now-famous personal letter to the presidents of all the government contracting corporations requesting "...a dollar's value for a dollar spent."[14]

Along with the outright closing of military installations, McNamara has taken further actions in an attempt to reduce wasted expenditure. He has de-emphasized the Cost Plus Fixed Fee (CPFF) contract, with the obvious result of forcing the adoption of efficient cost control methods on those companies which had previously been reliant on the CPFF convenience. There is no doubt that competition will sort out those whose cost control is ineffective.

Obviously then, the days of the crash program - free spending tactics are gone, possibly forever. Procurement men in industry as well as government will be quite sure they get their money's worth from every purchase. Indeed the emphasis in Washington has shifted to one of first

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14. Bidwell, Robert L., "Establishing the Need for an Effective Value Engineering Program", Journal of Value Engineering, August 15, 1964, p.23.

economic and, secondly, technological feasibility. In a statement concerning the soon-to-be submitted proposals for the Supersonic Transport (SST) contract, President Johnson indicated the primary importance of the economic consideration. The SST will have to be as tremendous an economic progression as it should be a technical one.[15] The basis for action in cost-reduction areas has, then, been established.

Causes of Time and/or Cost Overruns

However, the question of how to go about reducing costs still remains. Before remedial methods can be offered to solve the problem the main reasons for its existence must be recognized. The following are the most probable causes for the large discrepancies in time and cost estimates of large technical and engineering programs of the last 15 years:

- The difficulty of making accurate time and dollar estimates for activities involving technical uncertainty.
- The tendency to optimistically, or simply intentionally, under-bid.
- The absence of clear-cut, priority-assigned program goals.

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15. Lippke, James A., "The Shape of the Industry-Today", "Electronic Evaluation and Procurement", August, 1964, p.52.

. Inefficient planning and control methods, in general.

. Failure to recognize the interdependence of the time, cost, and performance variables germane to any project.[16]

The first four of the above reasons are generally agreed upon as predominant causes of time and/or cost overruns. However, it is conceivable that a management could well recognize the four and their undesirable ramifications and still slip up on one or two of them. It is the last reason that truly is the crux of the matter. The concept of an interdependence of time, cost, and performance variables is so important and essential to good management practice that it has caused a small revolution of thought in many managerial spheres of influence that is only now picking up momentum. This theory is important for two reasons. First, it provides the common denominator for the first four listed reasons, relating them so that management can more easily recognize and handle them. By recognizing and effectively acting on the time, cost, performance interdependence a management will also be efficiently handling the other four causes. (Of course, there are no management engineering tech-

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16. Miller, Robert W., Op.Cit., pp.13-14.

niques to overcome the effects of the intentional under-bid, but the concept of interdependence can permit a company to realize the degree of its under-bid quite accurately). Secondly, the interdependence concept is significant because it has shown the way for the development of extremely effective management techniques.

NEW MANAGEMENT ENGINEERING TECHNIQUES

The realization that a relationship among such variables could exist in management functions generated an interest among many involved in other more technical disciplines. Suddenly the mathematician and the electrical engineer became more respectful of the industrial and management engineering fields and a highly technical body of literature began to evolve. Many of the current management publications resemble mathematics or engineering textbooks; the Journal of the Operations Research Society of America is an example. Probability density functions, set theory, and schedule algebra are only some of the topics now being firmly entrenched in the management engineering body of knowledge. The concepts that the newly management oriented mathematicians and electrical engineers were manipulating in terms of their own disciplines were time, cost, and performance. However not only were those variables important of and by themselves but their time rates of change and response times of functions of them became of equal importance. It is here that probably the greatest contribution of the interdependence concept was realized. That concept supported by the treatment immediately provided it by other more technical disciplines revealed to the management engineering world and, indeed, the entire technical world the importance of planning and scheduling. All the new techniques boiled down to new ways to plan and schedule with logic, accuracy, and confidence.

The Program Evaluation and Review Technique

Of all the new developments in management methods of the last 10 years the greatest impact was created by the Program Evaluation and Review Technique (PERT). The Critical Path Method (CPM) is similar enough in theory and methodology to the PERT concept that, for the purposes of this paper both methods are implied by the single acronym, PERT. (Some authors today refer to the technique as PERT/CPM, explicitly indicating that present techniques represent a hybrid system).

PERT is predicated on the premise that planning and scheduling exist side by side as two discrete functions. The technique then consists of applying previously known concepts in a new manner; the result is a much clearer picture of a given situation. This can best be illustrated by an analogy involving radio and television. The television set uses the same components as the radio, but the arrangement of the components is altered so that video as well as audio can be received. In that context, PERT can be thought of as the video or picture of program management. By a specific, logical rearrangement of known, basic concepts management can proceed from voice or audio alone to the clarity of a visible project plan and schedule.[17]

The PERT technique can be used to plan and schedule any job wherein several different and separate activities must be performed, simultaneously and/or sequentially, in order to attain an objective. Therefore, one might assume that such diverse efforts as changing a tire, throwing a short pass to a tight end, cleaning false teeth, or building the Verrazano Bridge can be efficiently handled by PERT, and he would be absolutely correct. (As a matter of fact, one of the most learned and influential PERT analysts hints he planned his recent wedding via PERT). However it must be admitted that the changing of a tire or washing of one's face are simple enough tasks that profound planning is really not required. For all practical purposes an efficient job can be performed with a highly satisfactory result with little or no planning. This unfortunately is not so

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17. Martino, Op.Cit., p.8.

when the job is complex, with many not-too-apparent interrelationships; lackadaisical planning then results in highly undesirable results. The more complex a project, the greater the need for an effective, logical master plan with accurate, feasible schedules. Such plans and schedules are provided by PERT.

PERT and government contracts. PERT methodology is particularly well suited to military applications. The technique itself was created during the USN Polaris Missile Program, the largest, most complex weapon system in deployment. This huge project involved tens of thousands of people including highly trained submarine crews, Naval management people from the Special Projects Office, and civilian personnel from thousands of contributing industrial and governmental organizations. The weapon system hardware included the fire control and navigation systems, launching system, missile, and testing equipment. If any program required careful, extensive planning and clear-cut, logical schedules it was certainly this one.[18] In the words of Vice Admiral W. F. Raborn, Jr., the Deputy Chief of Naval Operations, "Although these Polaris management techniques were being widely copied by organizations in industry and government, we

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18. Raborn, Science, Technology, and Management, McGraw-Hill Book Co., Inc., 1963, pp.139-140.

were never satisfied. In early 1958, we set up an operations research team to develop the first system in history for measuring and predicting research and development progress. Within a few months PERT...was designed, pilot tested, and approved for application. The PERT system has won international acclaim as a 'management breakthrough' for saving time in the space age."[19] The Army and the Air Force lost little time in adapting the PERT approach to their needs. Lt. General F. S. Besson, Jr., the Commanding General of Army Materiel Command, has said "Some of the new management tools.... are especially helpful in the planning process and are being introduced into our project management structure, particularly PERT...."[20] The Ballistic Missile Early Warning System (BMEWS) and Minuteman Missile programs of the Air Force are both following plans and schedules developed using a PERT-like system.

Success in hardware programs. The praiseworthy comments of observers such as Admiral Raborn and General Besson and the flood of current literature given to PERT techniques attest to the remarkable success of the PERT tool. It has been employed over a wide spectrum of jobs,

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19. Raborn, Op.Cit., p.148.

20. Besson, Science, Technology, & Management, McGraw-Hill Book Co., Inc., 1963, p.100.

from the long term, very complex to the short time, slightly complex. Most of those programs had one thing in common; they all involved hardware or a product somewhere along the line. In most of the projects the product was indeed the most important feature; e.g. the Polaris missile, the Minuteman missile, and the radar sets of BMEWS.

SOFTWARE PROGRAMS

Not all large engineering projects culminate in the test and evaluation of a tangible product. Many projects funded by the government are strictly of the "software" variety, "....a billion dollar category aimed at solving specific military problems short of the development of experimental hardware. McNamara sees this, along with Research, as providing the 'pool of technical knowledge from which future weapon systems will be designed and designated'".[21] These efforts usually terminate with a final engineering report which incorporates the history of a problem, an in-depth analysis of the problem, and conclusions and recommendations which can resolve the problem.

Programs of this type are relatively new. It is

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21. Allison, David, "Defense Cutbacks", Science and Technology, October, 1964, pp.23,24.

only over the past 3 or 4 years that they have become common. The government allots funds for these programs in identical fashion and at the same time that it funds hardware projects. Therefore the cost-conscious attitude of the government is again reflected, this time in the realm of the software project.

SCOPE AND OBJECTIVE OF THESIS

To date, only minimal efforts have gone into the planning and scheduling of software programs. The reasons most commonly offered for this are:

- How does one go about planning and scheduling a job that is strictly a paper-work effort?
- How can an engineer or scientist estimate with a significant degree of certainty the time he will require to complete a theoretical analysis?[22]

At first these questions may seem to offer a valid argument. However, as previously mentioned, the government makes no distinction between hardware and software programs when it doles out the dollars. A certain amount of money and time is allotted for any software project. Regardless, then, of the nature of a job, the planning and scheduling of it still remain of paramount importance. It is a goal of this paper to show that software programs

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22. Miller, Op.Cit., pp.13-14.

respond favorably to modern planning and scheduling techniques.

For all its success PERT has seen virtually no utility in software programs. Therefore, it is the objective of this thesis to demonstrate the applicability of PERT methodology to projects of the software class. This thesis includes a discussion of the basic theory and mechanics of PERT, a detailed description of a specific software program presently under contract, and the generation of a PERT schedule for the program selected. The paper is concluded with observations by the author on the adequacy of the PERT scheduling method in the software domain and suggested improvements for future use.

Background of the Example Problem

The Tarzan Fire Control System consists of a tracking radar, guidance radar, and analog computer. The system has been installed aboard several USN cruisers and is intended to guide the Tarzan surface-to-air missile to intercept airborne targets.

Recently the Navy has been considering the replacement of the analog computer by a more reliable digital unit, the DC-18 computer. In order to determine how this computer would behave in the Tarzan Fire Control System shipboard environment, the concept of a "wrap around simulation" was conceived. A land based DC-06 digital computer was to be programmed to simulate ship and target motion, the guidance radar, the missile, and any special mode of operation included in the Tarzan system. The DC-06 was then to be connected to the DC-18, via appropriate cabling and wires, in such a way that the DC-18 could be tested as though it had actually been installed aboard ship. Hence, the DC-06 simulation program has been dubbed the "wrap around simulation." (Refer to Figure 1)[23]

A contract was awarded to the author's company for the purpose of providing a well controlled and conclusive checkout of the Tarzan digital operational program contained in a DC-18 computer by means of the wrap around simulation.[24]

Here then is a good example of a "strictly software" effort, and as such constitutes the real-world problem of this thesis to which the PERT planning and scheduling tool is applied.

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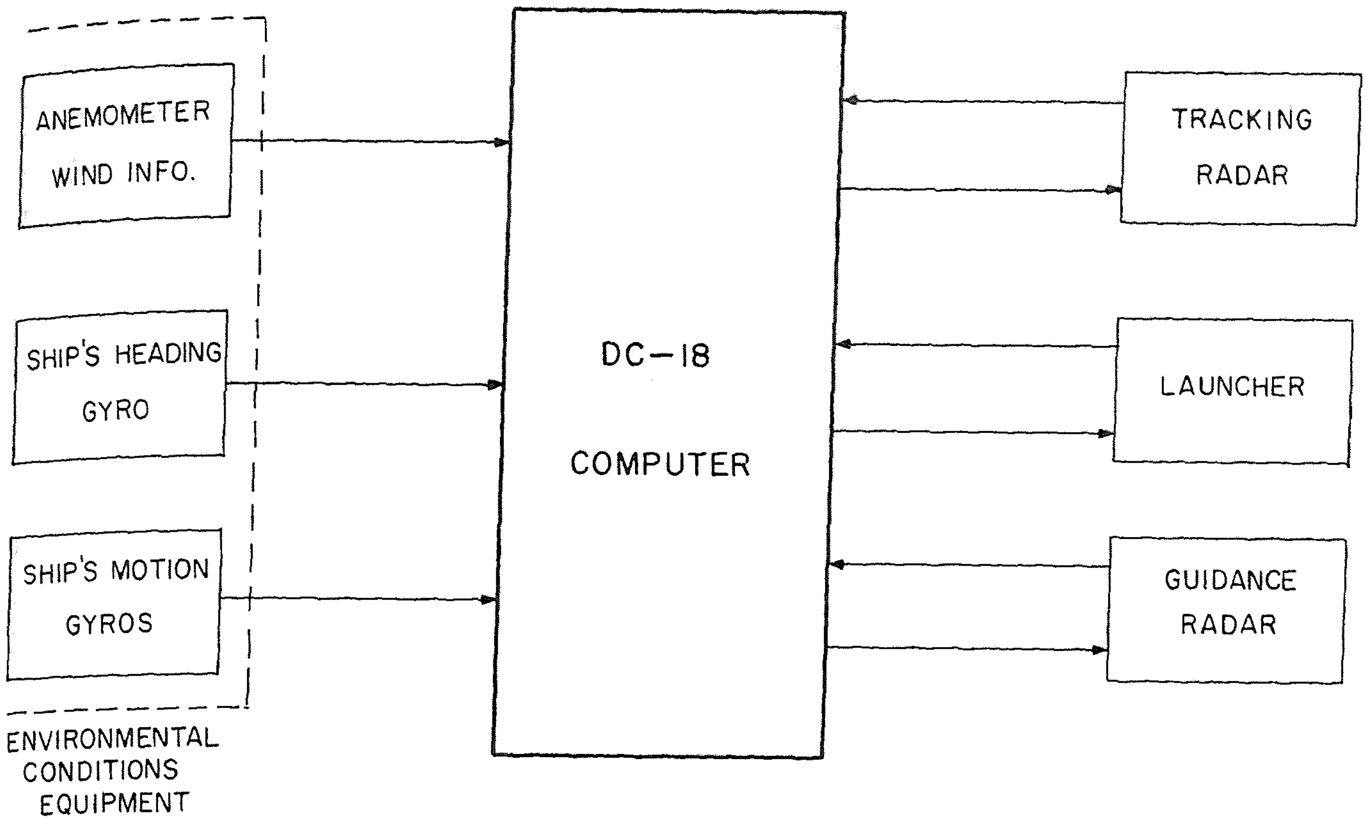
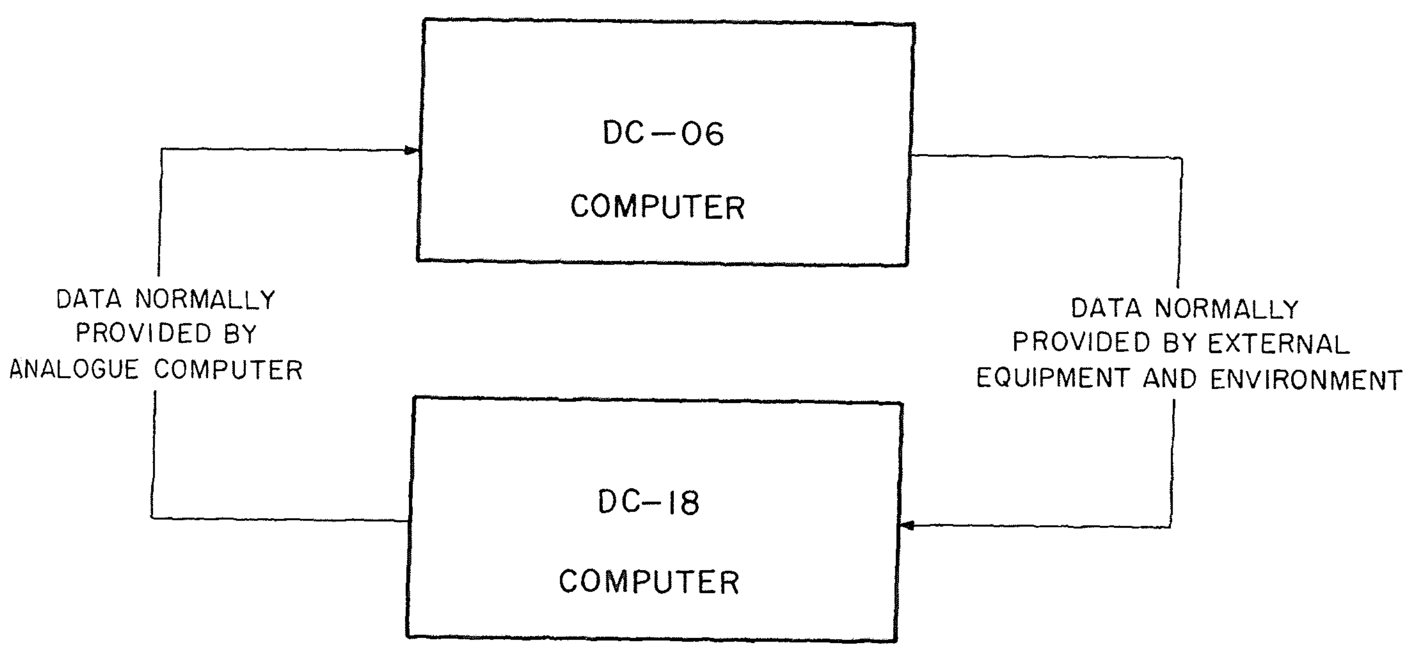
23. Fare, John, Surface Missile Systems Technical Instruction 270, Sperry 56, p.4 - (unpublished report).

24. Fare, Op.Cit., p.1.



DATA FLOW: PROPOSED SHIPBOARD CONFIGURATION



DATA FLOW: WRAP AROUND SIMULATION

FIGURE I

CHAPTER II : PERT THEORY

PERT-ORIENTED PLANNING

The first step in planning is to determine the necessary operations to be performed and then the sequence in which they are to be accomplished. An on-paper plan can then be set up as the working model from which the program will be carried out. The goodness of the plan will be determined by the smoothness and efficiency with which the project runs, as well as by its economic competitiveness.[1]

Prior to the advent of PERT, most planning techniques consisted of listing the required operations of a project in order of importance. Although the efforts expended were intensive and conscientious, many plans still failed. The factors most frequently responsible were:

- Omission of operations, particularly in large programs.
- Errors in the priority ratings of the operations.
- Plans could not forecast possible trouble spots; problems were solved <u>as</u> they occurred, not <u>before</u>.[2]

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1. Martino, <u>Op.Cit.</u>, p.18.
2. <u>Ibid.</u>

The PERT method has greatly minimized the effects of the foregoing problems, mainly because "... it enforces a discipline requiring far more objectivity than heretofore possible. It has provided a new way of thinking about projects."[3]

PERT Symbology

The basis of this new way of thinking is the arrow or network diagram. "The network displays an orderly, step by step series of actions which must be successfully performed in order to reach a specific, definable objective... a work flow diagram."[4] The network diagram is composed of two symbols: the arrow, which represents something that has to be done (activity, job, operation, etc.) and the circle which symbolizes an event. A rectangle or square may be used in place of the circle. Figure 2 is a network diagram for the extremely simple "project" of replacing a tube in a TV set.

The arrows in the network are the activities required to accomplish Project 1. Each arrow represents something that has to be done to effect completion of the entire task; a manual operation (Remove Bad Tube) or a parts procurement (Get New 5U4 Tube) are both properly

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3. Miller, Op.Cit., p.26.

4. Stires & Murphy, p.7.

NOTE: ARROWS REPRESENT ACTIVITIES
CIRCLES REPRESENT EVENTS

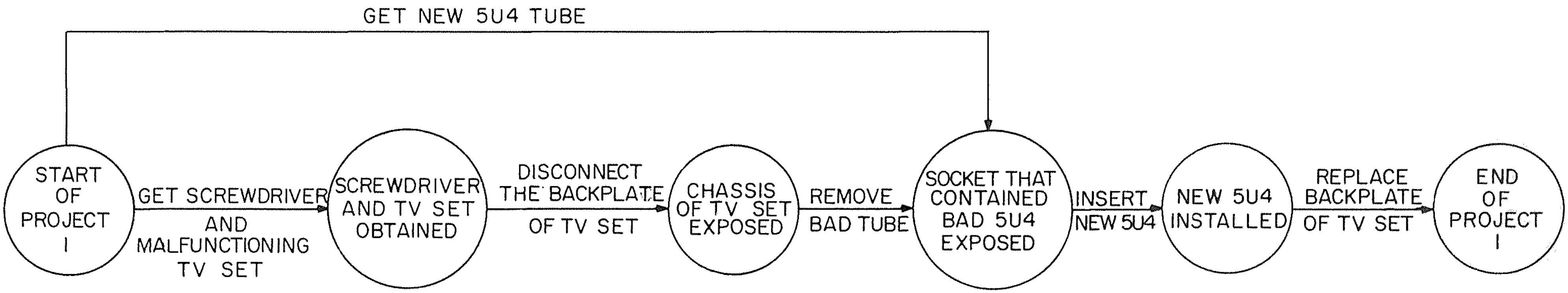

FIGURE 2

NETWORK DIAGRAM FOR PROJECT I: REPLACEMENT OF 5U4 TUBE IN TV SET represented by the arrow symbol.

The circles in the network diagram are the events of the project. An event is simply a "...highly identifiable point in time...";[5] for example, New 5U4 Installed and Chassis of TV Set Exposed describe easily recognized points of progress towards completion of Project 1.

Events. As projects increase in complexity it becomes more and more important to number the events of a network. For the simple task, Project 1, the events were simply numbered from left to right in ascending order. Event 1 is the starting event and Event 6 the terminating event for the network. If this network was a small part of a large network Event 6 would be referred to as a milestone or interface event. In such cases the event must occur in some other network with the same event number and description.[6]

In all PERT applications it is good practice to have a listing or dictionary of event definitions; such a tabulation becomes necessary as projects become more complex. This dictionary serves two useful purposes. First, it contains a clear definition of an event in a magnitude of detail that the space limitations of a PERT

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5. Miller, Op.Cit., p.30.

6. Ibid., p.31.

network could not permit. And second, it simplifies the network itself by requiring only a number to appear in a circle to identify an event. A listing of event definitions and the corresponding PERT network for Project 1 is shown in Figure 3.[7]

Activities. In modern PERT technology, activities are identified by their predecessor and successor event numbers. For example, in Project 1, activity "Remove Bad Tube" could more simply be described as activity "3-4."

Each activity of a network carries with it the time required for its accomplishment, its "elapsed time" or "duration." This time may be in hours, days, weeks, or even months, dependent on the constraints and requirements of a specific project.

An activity also implies the expenditure of resources, whether manpower or material or both. For example, activity 2-3 of Project 1 requires 1 man and 1 screwdriver for an elapsed time of about five minutes. Both manpower and material are expended during that activity. Activity 3-4 requires only manpower (assuming the tube is not frozen in its socket), and would consume only about a half-minute.[8]

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7. Ibid., p.32.

8. Ibid., p.32.

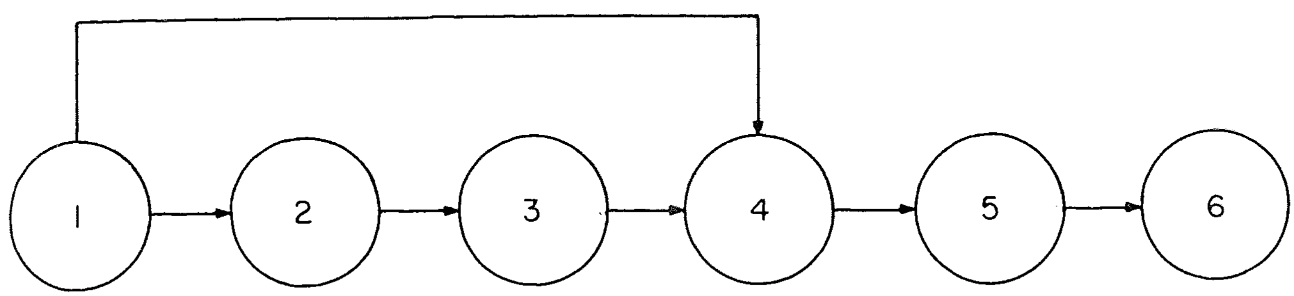

FIGURE 3

EVENT DICTIONARY AND SIMPLIFIED PERT NETWORK FOR PROJECT I

1. Start of Project 1.
2. Screwdriver and TV Set Obtained (Set should be repaired at its location).
3. Chassis of TV Set Exposed (Reference: Tube Location Chart on Backplate of Set).
4. Socket that Contained Bad 5U4 Exposed.
5. New 5U4 Installed.
6. End of Project 1.

Each activity in Project 1 could be analyzed and a resource expenditure and elapsed time be established for every one. Although the expenditures of resources and time may be very small, as in the case of activity 3-4, they nonetheless are real, measurable quantities. However, there does exist a type of activity which requires neither time nor resources; this artificial device is most commonly referred to as the dummy activity. The dummy activity, which has a duration of zero time, "...is used to indicate a constraint not requiring resources...."[9] The dummy is further employed "...to keep the logical sequencing of jobs, and their interrelationship, correct."[10] Examples of the use of this type of activity are included in the next section which outlines the basic rules of network diagramming.

RULES OF NETWORK DIAGRAMMING

"In applying PERT...to a project, arrow diagramming is the first but most important phase....The need to prepare a completely accurate arrow diagram cannot be stressed too much."[11] Therefore, a set of rules is herein presented, with discussions and examples where required.

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9. Ibid., p.33.

10. Martino, Op.Cit., p.25.

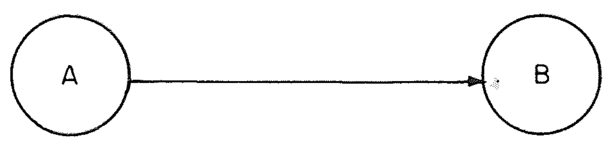
11. Ibid., p.51.

RULE 1. Each activity is represented by one, and only one, arrow.

The length of the arrow is of no importance. Its direction is equally insignificant. Its importance lies in its symbolic representation of an activity and the visual indication of the duration of the activity. Time flows from the tail to the head of the arrow representing the duration of a job from start to finish.

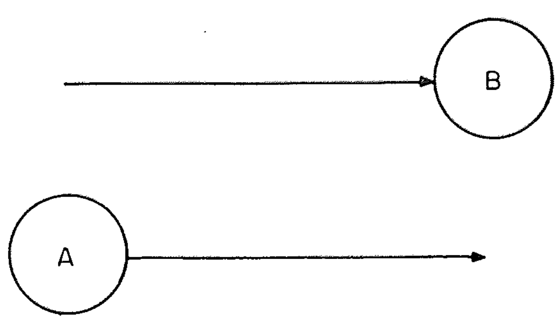
RULE 2. Each activity must have a predecessor and successor event.

This rule requires that an activity must begin and end at easily identifiable points in time. Any activity in a PERT network can be isolated to appear as:



Here the arrow represents activity A-B with the job starting at event A and ending at event B.

An activity could not be represented in either of the two following ways:



The first representation has no specific beginning and the second no end; such symbology has no place in a logical system.

. RULE 3. No activity can start until its predecessor event has been established.

This is the most important rule of the PERT technique. It could be restated "...no event may be considered complete until all activities leading into it have been completed."[12] Both forms of this rule should be fully recognized and appreciated when considering network topology. This rule demands clear activity and event definition and enforces a depth of analysis to determine and illustrate on the PERT chart the true constraints of a project.

. RULE 4. Dummy activities are introduced as required to maintain network logic.

Consider a program, Project 2, consisting of four jobs, activities A, B, C, and D. Activities B and C both depend on activity A but are independent of each other. Further, activity C also depends on job D. Initially one might set up the diagram:

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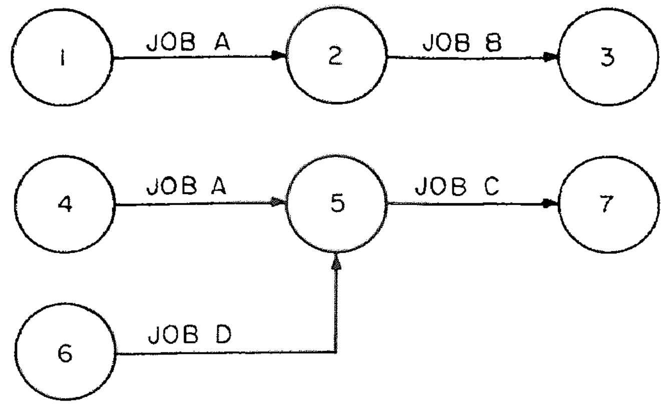
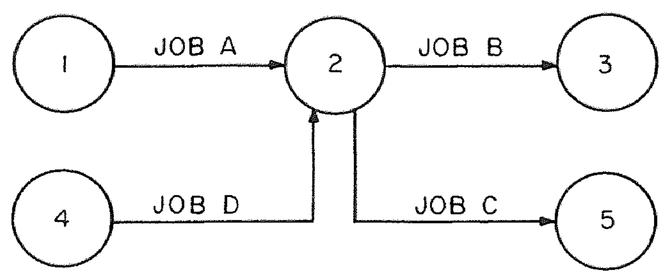
12. Miller, Op.Cit., p.34.

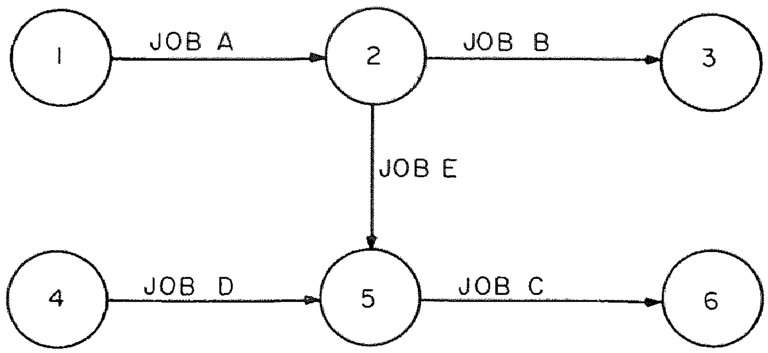


The above is incorrect because it violates Rule 1; Job A is represented by two arrows, not one.

The network could then be rearranged to appear as:



The network above is incorrect because it portrays Job B as dependent on Job D, not a true system constraint. How then can one construct a network that fulfills the system constraints and Rule 1 as well? The introduction of a dummy activity, Job E, solves the problem.



Job E is the dummy activity utilized in Project 2. It has no duration (elapsed time = 0) and entails no resource expenditure; in short, it does not exist in the real world. Yet its presence as a symbol in the network permits the logic to be consistent with the system restraints of Project 2.

The four rules discussed in this section are basic to network diagramming techniques. A full understanding of each one, with respect to its theory and applicability, is mandatory for a PERT analyst.

TIME IN PERT NETWORKS

Up to this point in the chapter PERT has been presented as a planning tool. However, by the introduction of time estimates for each activity in the network "...it is possible to expand what would be only a relatively unsophisticated planning method, into a powerful control system...."[13]

When a network has been developed to the point where the PERT analyst feels he has a working model (Figure 3 is an example) attention can then focus on time estimating and the assignment of those who are to be responsible for the estimates.

Source of Estimates

The effectiveness of a PERT network is predicated on the soundness of its time estimates. Therefore it is vital to a project to assign the responsibility of the time estimates to the most appropriate personnel.

Time estimates are associated with activities only. Since events are simply checkpoints in time, no time is expended by an event and no estimates are required. For the special case of the dummy activity no time estimates are necessary since, by definition, the duration of a dummy is zero time. Therefore the consideration of time is applicable to the activities of a project, only.

Since each activity of a program will be performed by one person or group of persons, the time estimates for that activity should be obtained from that person or group. The person(s) who actually does a job can offer the most realistic estimates concerning its duration.

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13. Stires and Murphy, Op.Cit., p.23.

Any other source including first-line supervision is almost certain to introduce further bias and error. Higher management, being even farther removed from manual operations, will probably inject still greater error. Management's function here is the assignment of responsibility. The first-line supervisor or higher must delegate a knowledgeable and responsible worker to an activity; the estimates of such an employee can then be taken as the most realistic available.

Inherent Assumptions

Several arbitrary assumptions intrinsic to time estimating must be fully recognized and complied with throughout the development of a PERT chart. A consideration of these assumptions can lead to a set of rules which can aid the estimator in his extremely important function.

Firstly, the estimator must consider the resources which will be consumed by his activity, since the amount of resources involved will have a direct effect upon the duration of the job. Once he establishes the amount of resources required, he should assume a constant level of expenditure. This assumption will certainly turn out to be false in many cases, but it is the most plausible approach and constitutes a good starting point.[14] In

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14. *Ibid.*

addition, if all activities are estimated assuming a constant level of expenditure, management is afforded a visual indication of possible trouble-spots requiring special attention.

For example, a project could be estimated on the assumption that two, and only two, men will perform each activity. An analysis of the resultant network could indicate that one or more activities could not realistically be handled with only two men. Perhaps six or seven would be required; maybe two would do until the activity was half completed, then 10 men might be needed immediately. Maybe two men on one activity would be overstaffing a job and one man might have nothing to do. Situations such as these would be illuminated by adherence to the assumption of a constant level of expenditure. If, on the other hand, estimators were allowed to operate on a basis of variable levels, only confusion and ineffective networks can result.

In estimating manpower requirements a standard time unit should be assumed. In the missile and space industry the eight hour day, five day week is the most commonly employed standard. Regardless of the unit chosen, it is paramount that each activity be estimated in terms of that unit only. Considerations for holidays, vacations, or overtime should not be allowed to influence the time estimate.[15]

Last, an estimator should assume that the activity in question is the only job he is to do. His estimate will then be based on the most realistic time value, unburdened by the effects of time-sharing. Most important of all, he should not let the duration of one activity bias his thinking in regard to any other activity. Later, when the estimates for all the activities of a project are on paper, management can and should weigh estimates relative to one another. But this action should be done with the entire project in view, never before.[16]

The Three Time Estimates

"If management knew with certainty the exact amount of time necessary to accomplish an activity, there would be no need for estimates or management."[17] Digital computers could be programmed to construct PERT charts if estimates could be considered 100 per cent certain. Of course, nothing is certain in the real world; inherent in every time estimate is a degree of uncertainty. There are many unforseeable factors which could severely delay

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15. Ibid.

16. Ibid., p.25.

17. Ibid.

an activity or, on the other hand, act as catalysts and speed it up beyond all reasonable predictions. In most of the missile and space projects there are "...a good many activities, typically in the early phases of development engineering and in all testing phases, where a significant amount of time uncertainty comes to the fore during the estimating process, i.e., where no standards or comparable history exist."[18] The PERT method includes a recognition of uncertainty by classifying it in a standardized reference frame so that a project can be managed on a predictable basis.

Once an estimator is thoroughly familiar with his assigned activity he actively recognizes the uncertainty in its duration by describing the job in three ways. Each description culminates in a time estimate; therefore, the estimator concludes his effort by assigning three time estimates to an activity. These estimates are referred to as (1) Optimistic, (2) Most Likely, and (3) Pessimistic. The definitions of each are as follows:

> Optimistic: An estimate of the minimum time an activity will require. This will result only if everything goes unexpectedly well with unusual good luck.[19]

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18. Miller, Op.Cit., p.39.

19. Ibid., p.41.

- Most Likely: An estimate of the normal time an activity will require. This is the time that would occur most frequently if the activity were performed a large number of times. The common standard in industry is to assume performance of the activity one hundred times. The estimate established is the one which the estimator predicts will occur most frequently if the activity were repeated one hundred times.[20]
- Pessimistic: An estimate of the maximum time an activity will require. This would result only if everything that could possibly go wrong did go wrong. However, the possibility of catastrophic events such as strikes, fires, power failures, etc. should not influence this estimate. The principal factors here should be those over which the estimator has control but could mismanage in some way. For example, the possibility of initial failure and second start should be considered when making this estimate. It should further include an allowance for an excessive amount of bad luck.[21]

Expected Activity Time

Once the three time estimates are obtained the

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20. Stires and Murphy, Op.Cit., p.26.

21. Miller, Loc.Cit.

question of how to use them most effectively still remains. This was the problem faced by the original PERT research team. The approach taken was to find a general probability distribution which best described the system constraints of the PERT method. The analysis presented here is consistent with the philosophy adopted by that operations research team.

The beta distribution. The general probability distribution must reflect the following characteristics:

1. The probability of realizing the Optimistic Time, to, should be very small. Common practice in industry is to establish this probability at 0.01 or one chance in one hundred.
2. The probability of realizing the Pessimistic Time, tp, should be equally as small, i.e. 0.01.
3. The distribution is unimodal with the Most Likely Time, tm, being the modal value, free to move between the two extremes. This parameter has a high probability of occurrence relative to the other two.[22]

Extensive investigation by the PERT research team disclosed that such data best fitted a Beta Distribution. Figure 4 is a typical beta distribution which might

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22. Stires and Murphy, Op.Cit., p.28.

represent the span of possible elapsed times for an activity. The peak of the curve occurs at t=tm, the most likely time. For the curve in Figure 4, tm is closer to to than it is to tp; i.e. the most likely time is closer to the optimistic time than it is to the pessimistic estimate. Therefore the distribution is skewed to the right. Since the required characteristics enumerated above stipulate that tm is free to move relative to to and tp, the curves of Figure 5 are also possible. The skewed left curve illustrates the situation when tm is closer to tp, or the most likely time is closer to the pessimistic time. The curve of no skewness portrays the special case when tm is equidistant from to and tp; under those circumstances the most likely time occurs at the halfway point between the optimistic and pessimistic time estimates.[23]

Mathematical analysis. Accepting the beta distribution as representative of the problem, it is possible to derive one time, te, which is the expected time of an activity, based on the three time estimates for the activity.

The mathematical expression for the beta distribution is:*

$$f(t) = K(t-a)^{c} \quad (b-t)^{d} \qquad \text{Eq. (1)}$$

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23. Ibid., pp.32-33.

* Source of derivation: Miller, Op.Cit., pp.199-201.

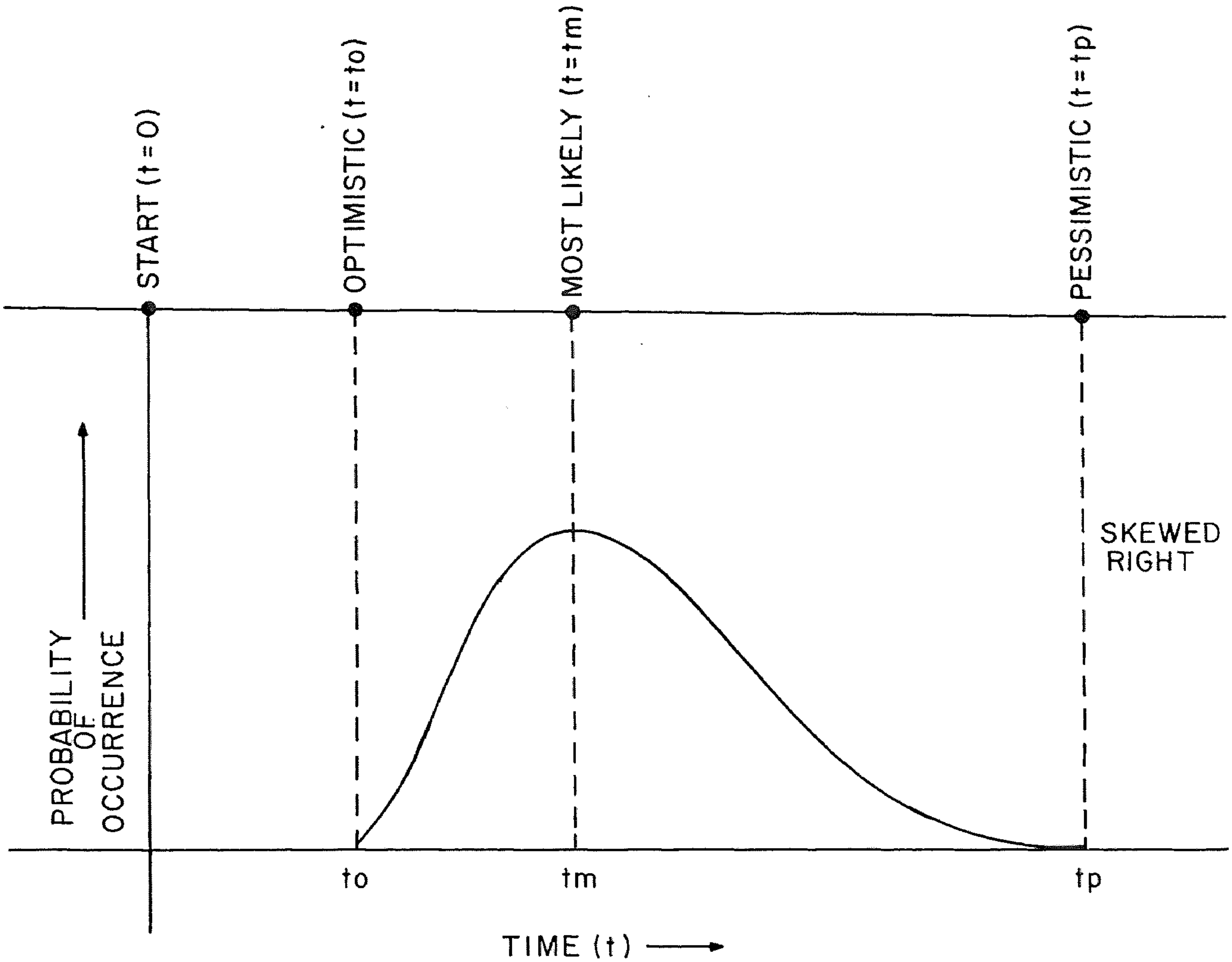

FIGURE 4
TYPICAL BETA DISTRIBUTION [23]

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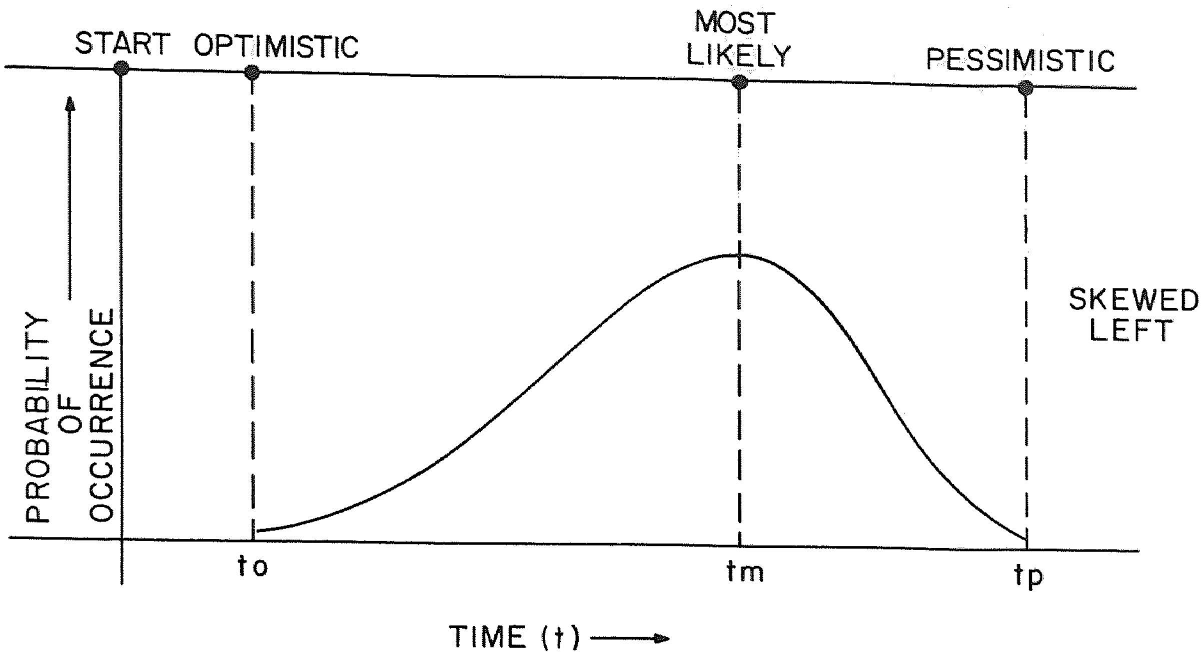
23. PERT Summary Report, Phase I, Special Projects Office, Bureau of Naval Weapons, Dept. of the Navy, Washington, D.C., Government Printing Office, Catalog No. 217.2, pp.94-948,1960.



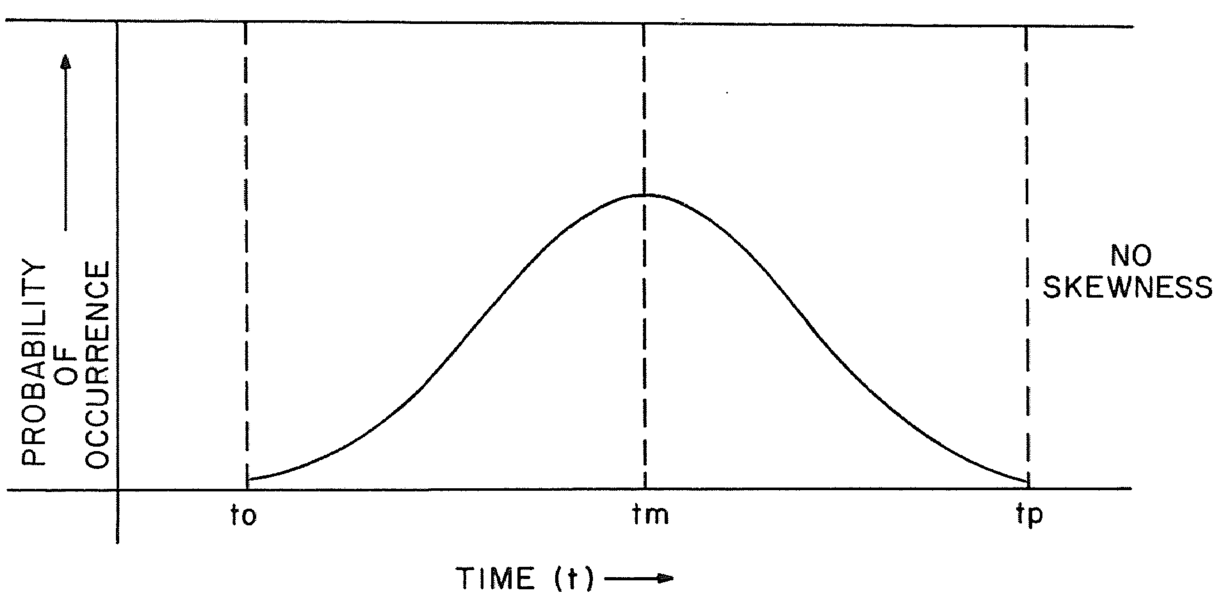


FIGURE 5

POSSIBLE BETA DISTRIBUTIONS

Where: $a = t_o$, the optimistic time

$m = t_m$, the most likely time

$b = t_p$, the pessimistic time

$K = f\ (a, m, b)$

$c = f\ (a, m, b)$

$d = f\ (a, m, b)$

Since the expected time, t_e, must fall somewhere between a and b, the value of the probability density function must be unity. Therefore the range of the distribution must be equal to one, or:

$$b - a = 1 \qquad \text{Eq. (2)}$$

The abscissa is then rescaled to a general parameter, x, where:

$$x = \frac{t - a}{b - a} \qquad \text{Eq. (3)}$$

The mode, m, can then be described in terms of the new scale as:

$$r = \frac{m - a}{b - a} \qquad \text{Eq. (4)}$$

Substitution of c and d into Eq. (4) results in a modal expression:

$$r = \frac{c}{c + d} \qquad \text{Eq. (5)}$$

The expression for the variance, σ^2, of a beta distribution rescaled to the x-abscissa is:

$$\sigma x^2 = \frac{(c + 1)\ (d + 1)}{(c + d + 2)^2\ (c + d + 3)} \qquad \text{Eq. (6)}$$

The first of two assumptions upon which this entire analysis relies follows:

> Assumption 1: The standard deviation, σ, is equal to one-sixth of the range.

This approximation is widely used in all types of statistical analyses and experience has proved it a reliable and useful estimate. Therefore, the simplified expression for σx is as follows:

$$\sigma x = \frac{\text{Range}}{6} = \frac{b-a}{6} = \frac{1}{6} \qquad \text{Eq. (7)}$$

Equating Eq. (6) to the square of Eq. (7):

$$\frac{(c + 1)\ (d + 1)}{(c + d + 2)^2\ (c + d + 3)} = \left(\frac{1}{6}\right)^2 = \frac{1}{36} \qquad \text{Eq. (8)}$$

Substituting Eq. (5) into the above expression:

$$d^3 + (36r^3 - 36r^2 + 7r)\ c^2 - 20r^2\ d - 24r^3 = 0 \qquad \text{Eq. (9)}$$

The expected value of x, E(x), for the beta distribution is:

$$E\ (x) = \frac{c + 1}{c + d + 2} \qquad \text{Eq. (10)}$$

By substituting the time estimates a, m, and b into

Eqs. (5), (9), and (10), the solution for E(x) or te will be obtained. However, the solution of the cubic equation of Eq. (9) for every activity in a network could bog down the entire effort and introduce an undesired new area for mistakes. Therefore several values of r and E(x) can be computed and a plot of r versus E(x) constructed. Such a plot is shown in Figure 6.

The second assumption is now imposed:

Assumption 2: The relationship between r and E(x) is linear.

Analysis of the curve justifies this assumption as a realistic one. It is then easy to relate r to E(x) by utilizing the y = mx + b formula for a straight line. Hence:

$$E(x) = \frac{2}{3} r + \frac{1}{6} = \frac{4r + 1}{6} \qquad \text{Eq. (11)}$$

Substituting Eqs. (3) and (4):

$$\frac{4 \left(\frac{m-a}{b-a}\right) + 1}{6} = \frac{te - a}{b - a}$$

Reducing the above results in the following expression for te, the expected activity time:

$$te = \frac{a + 4m + 6}{6} \qquad \text{Eq. (12)}$$

The expected activity time, te, can be thought of as

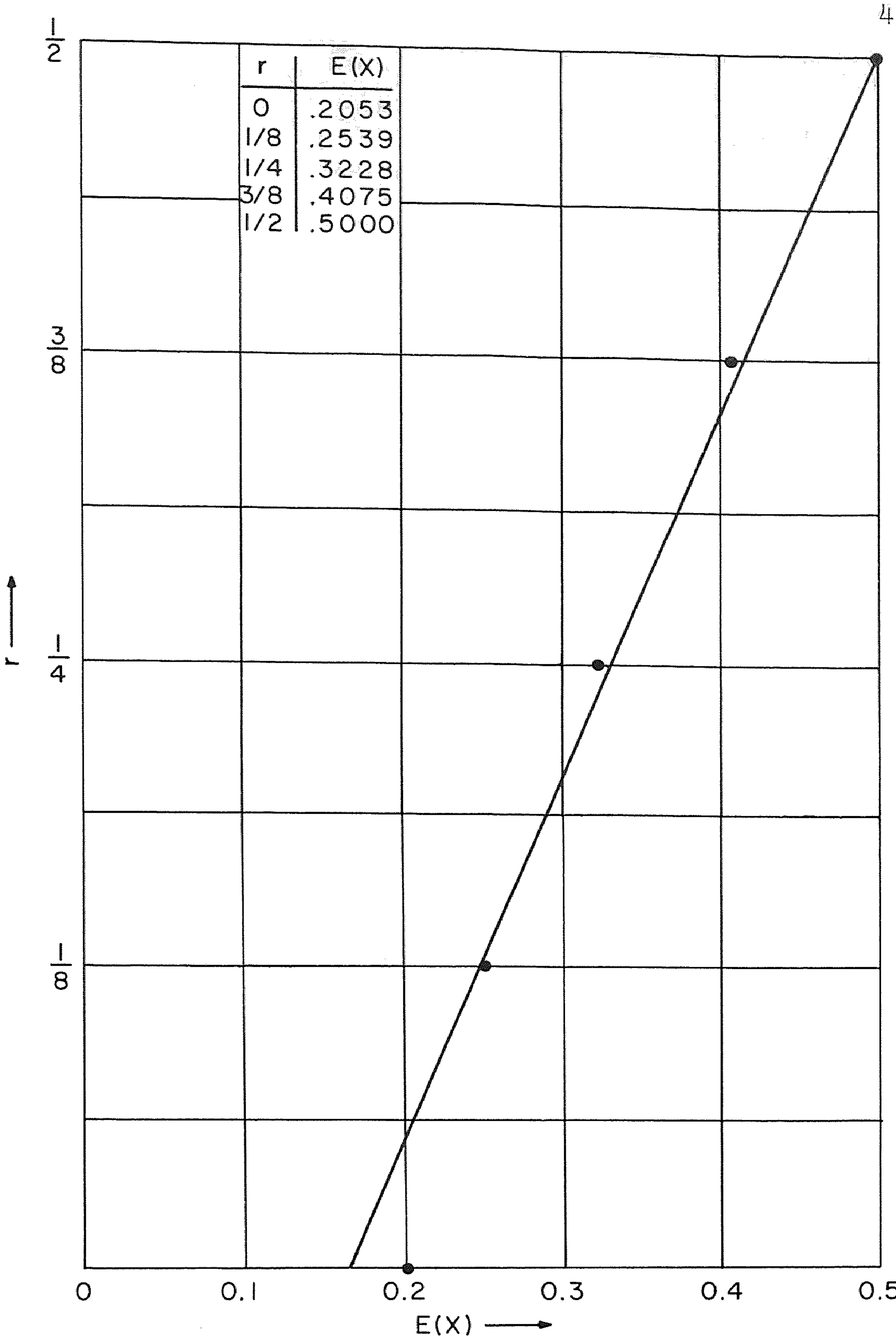


FIGURE 6
STRAIGHT LINE APPROXIMATION

a weighted statistical average of the three time estimates, "...such that there is a 50-50 chance of completing the activity at this time."[24]

Assignment of expected activity times to project 1. When the time estimates for all activities of a project are obtained, the te's for each activity can be computed using Eq. (12). The te values may be calculated by a computer or by hand, depending on the size of the project. Project 1 of this paper, for example, is a small project which would not require the costly services of an electronic computer. Its te values could easily be calculated by hand. For instance, consider activity 5-6 with time estimates as follows:

$$a = to = 2 \text{ minutes}$$

$$m = tm = 5 \text{ minutes}$$

$$b = tp = 30 \text{ minutes}$$

Substituting into Eq. (12):

$$te = \frac{a + 4m + b}{6} \quad \frac{2 + 4(5) + 30}{6} = \frac{52}{6}$$

$$te = 8.67 \text{ or } 8.7 \text{ minutes}$$

The expected time of activity 5-6 is 8.7 minutes; the te's of the other activities could be calculated in a

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24. Stires and Murphy, Op.Cit., p.30.

similar manner and the values placed on the network diagram as shown in Figure 7. The diagram is now a quantitative guide as well as a logic control.

NOTE: ALL TIMES
IN MINUTES

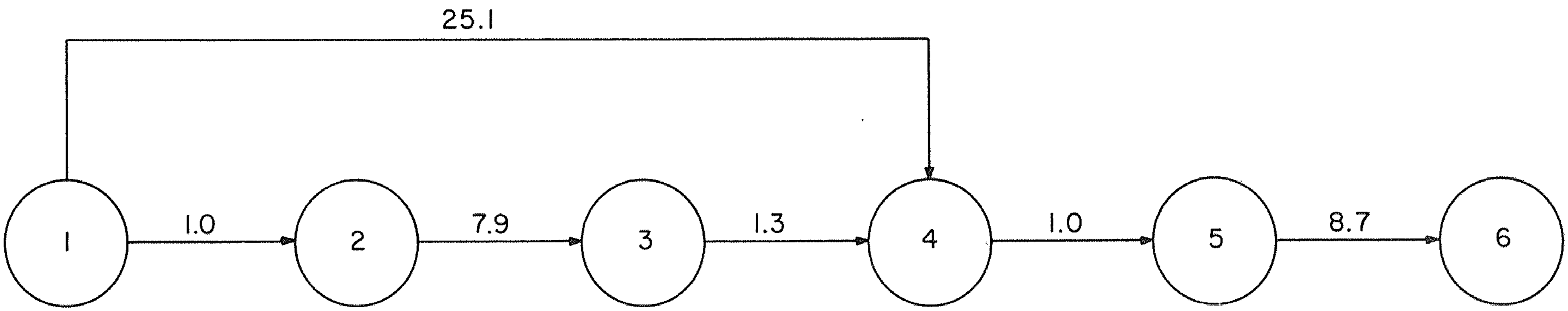

FIGURE 7
NETWORK FOR PROJECT I WITH EXPECTED ACTIVITY TIMES

CHAPTER III : PERT CALCULATIONS

Up to this point, the theory and philosophy of the PERT approach have been shown to provide:

- A logical master plan in network form which displays the interdependence of all the activities of a project.
- A statistically derived expected duration for each activity.

In this chapter simple arithmetic analyses and procedures are presented which utilize and build upon the above information so that the ultimate objective of the PERT method is realized; viz., "...a schedule giving the calendar date on which each job will start."[1]

ACTIVITY STARTING TIMES

When analyzing an activity for its starting time, it is often discovered that there is some variation in possible start times. It is quite conceivable that an activity might start any time within a specific time range and not affect the completion date of the overall project. For example, consider the situation on the following page:

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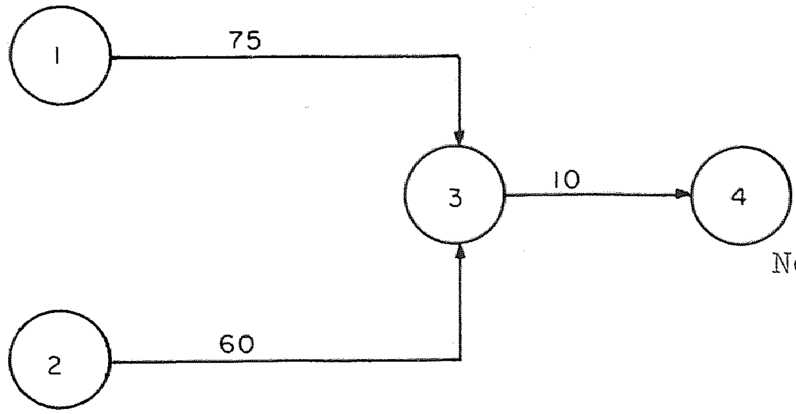
1. Martino, Op.Cit., p.58.



Note: time in days

In the above diagram activity 3-4 is dependent upon the completion of activities 1-3 and 2-3. From the activity durations shown in the network it is apparent that activity 3-4 can start no sooner than 75 days after the start of activity 1-3. Furthermore, activity 3-4 can start no sooner than 60 days after the start of activity 2-3. If events 1 and 2 occur at the same point in time, it can be seen that activity 2-3 can start as late as 15 days after activity 1-3 and no effect will be had on the overall network. Using specific calendar dates, this means that if activity 1-3 started on April 1, activity 2-3 could safely start any day from April 1 through April 16, with no delaying effects on the project.

In the example above it was pointed out that activity 1-3 could safely start any one of the first sixteen days in April. Of all those possible starting dates the first, April 1, and the last, April 16, are the most significant. They represent the Earliest Start and Latest Start times, respectively, for the activity.

Earliest Activity Start

The earliest activity start is simply the earliest date on which an activity may begin. To determine the earliest starting date for each activity in a project, two things are required:

. The network diagram including expected activity times, as developed in Chapter II.

. A starting date for the project.[2]

The first of these requirements was discussed in Chapter II.

The second requirement, a project starting date, can be handled in either or both of two ways. Firstly a definite calendar date may be specified. That date is, of course, important but it does not have to be known. The second and more general method is to designate the starting date of the project as "zero-time." The procedure then is to develop activity start dates as numbers of time units relative to the zero-time base. It is a simple matter to transpose the numbers of time units to calendar dates whenever such information is required.[3] Therefore, there are two excellent reasons for using the zero-time method for specifying a project starting date:

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2. Ibid., p.59.

3. Ibid.

- The lack of a calendar date for the start of the project in no way can delay the development of a PERT analysis.
- It is far more convenient to work in relative numbers rather than calendar dates, particularly if revision is required.[4]

The quantity E. Consistent with the Rules of Network Diagramming set up in Chapter II, the earliest starting time for an activity is directly associated with the completion of its predecessor event. Rule 3 requires that an activity can not start until all the activities terminating at its predecessor event have been completed. Thus, in the example of page 51, activity 3-4 cannot start until both activities 1-3 and 2-3 are completed, or Event 3 has been "completed."

The term "event completion" indicated in the previous paragraph is commonly used in industry today. However, it can be confusing since an event time duration is inadvertently implied. When a PERT analyst uses the term he actually is referring to "the completion of all the activities leading into the event." Rather than carry such a cumbersome expression, he uses a shorter albeit somewhat misleading term.

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4. Ibid.

An analogous situation exists regarding earliest start times. The phrase "the earliest starting time for all the activities beginning at event A" is frequently encountered during a PERT analysis. The term "event start" could be substituted but again the time concept is implied. A simpler method would be to "...let E represent this phrase. Then, through a subscript representing the event, the meaning is perfectly clear and the quantity is completely defined."[5] Therefore, the earliest start times for all the activities starting at, say, event 3 would be E3.

Calculation of E's for project 1. An example showing how E values are obtained for a network is essential; therefore, let us again consider Project 1 and discuss the necessary manipulations in detail.

First, a three-column tabulation should be set up with the headings, Activity, Duration, and E. Then, using Figure 7 as reference, the Activity and Duration columns can be filled in. The determination of the E's proceeds as follows:

. Assign E1 equal to zero-time; i.e., the earliest starting times for activities 1-2 and 1-4 are arbitrarily set to a zero base-line.

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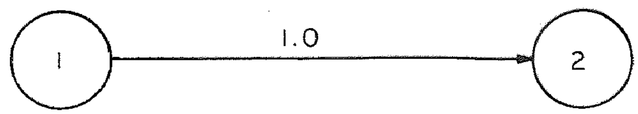
5. Ibid., p.64.

. Consider Event 2:

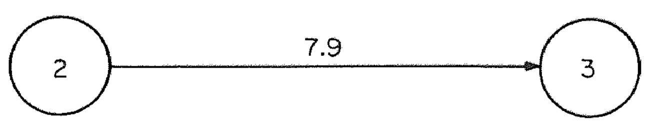


Event 2 is the terminating point for activity 1-2; no other activity has this event as a successor. Therefore the earliest possible starting times for any activities starting at this event are dependent upon the duration of activity 1-2 and its starting time, or:

E2 = E1 + Duration of Activity 1-2

E2 = 0 + 1.0 = 1.0

. Consider Event 3:

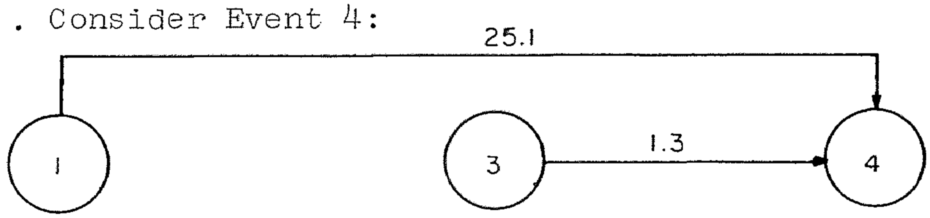


Event 3 is the successor event for activity 2-3; therefore:

E3 = E2 + Duration of Activity 2-3

E3 = 1.0 + 7.9 = 8.9

. Consider Event 4:



Event 4 is the successor event for two activities; jobs 1-4 and 3-4. Computing an E4 based on activity 3-4:

$(E4)_1$ = E3 + Duration of Activity 3-4

$(E4)_1$ = 8.9 + 1.3 = 10.2

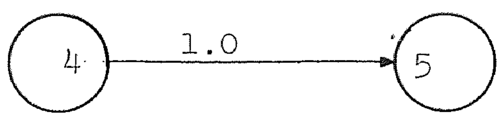
Computing an E4 based on activity 1-4:

$$(E4)_2 = E_1 + \text{Duration of Activity 1-4}$$

$$(E4)_2 = 0 + 25.1 = 25.1$$

Quite obviously $(E4)_1$ does not equal $(E4)_2$. Physically the implication is that activity 1-4 consumes more time than do the combined efforts of activities 1-2, 2-3, and 3-4. Since Rule 3 of Network Diagramming forbids the start of an activity prior to the completion of its predecessor event, E4 must equal $(E4)_2$, the larger of the two computed values. Therefore: E4 = 25.1.

. Consider Event 5:

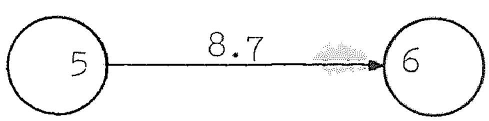


Event 5 is the successor for activity 4-5 only; therefore:

$$E5 = E4 + \text{Duration of Activity 4-5}$$

$$E5 = 25.1 + 1.0 = 26.1$$

. Consider Event 6:



Event 6 is the successor event for activity 5-6; therefore:

$$E6 = E5 + \text{Duration of Activity 5-6}$$

$$E6 = 26.1 + 8.7 = 34.8$$

As Event 6 is the terminating event of the network, E6 actually represents the earliest finish for the project.

Table 1 is the completely filled-in tabulation showing the results of the preceding calculations.

Latest Activity Start

The latest activity start is the latest possible date on which a job may begin. Delaying an activity past this date will disrupt the harmony of the remainder of the network and the earliest and latest starting dates originally calculated will no longer be effective guideposts.

The quantity L. Again it is possible to relate an activity characteristic to an event. The latest start of an activity can also be thought of as the latest finish of all the activities terminating at its predecessor event. Therefore, the latest finish date of all the activities terminating at an event will be designated by the letter L, and again subscripts are used to describe a specific event. For example, the latest finish of all the activities terminating at event 6 would be L6.

Calculation of L's for project 1. The L's for Project 1 are calculated in a manner similar to that for the E's, with the exception that the calculations begin at

ACTIVITY	DURATION	E
1-2	1.0	0
1-4	25.0	0
2-3	7.9	1.0
3-4	1.3	8.9
4-5	1.0	25.1
5-6	8.7	26.1

TABLE 1

EARLIEST START TIMES FOR ACTIVITIES OF PROJECT 1 the last event and progress backwards through the network.

The first consideration is to the L value for the last event. This value is arbitrarily set equal to the E for that event since there is no reason to delay a project anymore than necessary. "While any condition whatsoever could be imposed as the final project completion time, selecting a duration longer than necessary would, obviously, not be realistic."[6] Therefore:

$$L6 = E6 \; ; \; L6 = 34.8$$

It is a simple task to set up the following equations:

L5 = L6 - Duration of Activity 5-6 = 34.1 - 8.7 = 26.1

L4 = L5 - Duration of Activity 4-5 = 26.1 - 1.0 = 25.1

L3 = L4 - Duration of Activity 3-4 = 25.1 - 1.3 = 23.8

L2 = L3 - Duration of Activity 2-3 = 23.8 - 7.9 = 15.9

The determination of L1 presents a problem similar to that confronted when calculating E4. Event 1 is the starting event for two activities, as shown on the following page:

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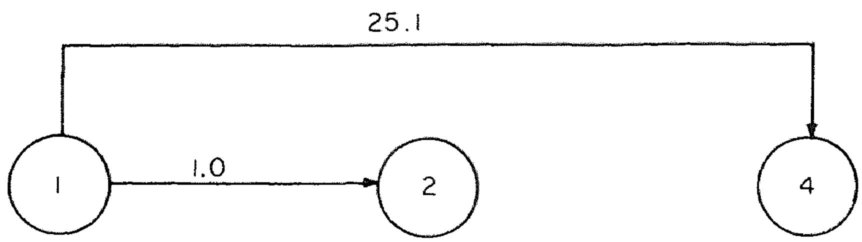
6. Ibid., p.84.



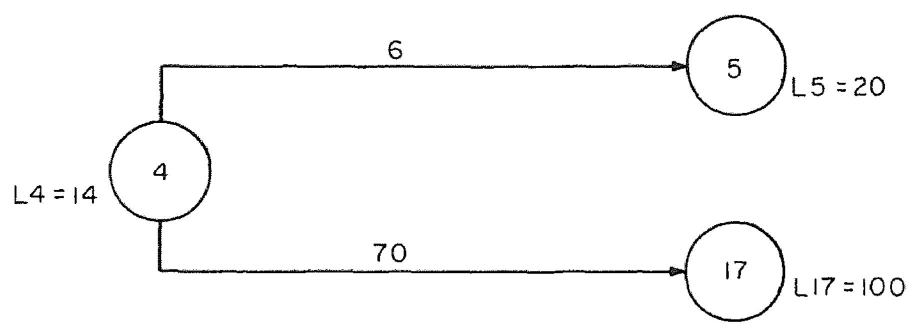
Two values of L1 can be calculated:

$(L1)_1$ = L2 - Duration of Activity 1-2 = 15.9 - 1.0 = 14.9

$(L1)_2$ = L4 - Duration of Activity 1-4 = 25.1 - 25.1 = 0

Here again, calculations indicate two values, only one of which is correct. If L1 were equal to $(L1)_1$, or 14.9, activity 1-4 could start as late as date 14.9. The earliest starting date for activities starting at event 4 would then be 14.9 + 25.1 = 40.0. However, a check of the previous computations reveals that the latest start time for any activities out of event 4 is 25.1. Since 40.0 exceeds 25.1, L1 cannot be equal to $(L1)_1$. If L1 were equated to $(L1)_2$, or zero, activities 1-4 and 1-2 could start at time zero. (Indeed, as will be discussed later, at least one of the two must start at zero time.) The network arithmetic substantiates setting L1 = 0. The earliest start of an activity from event 4 based on activity 1-4 would be 0 + 25.1 = 25.1, which does not exceed the latest possible start from that event. The earliest activity start from event 2 based on activity 1-2 would be 0 + 1.0 = 1.0, which does not come close to the latest starting date for that event. Therefore setting $L1 = (L1)_2 = 0$ satisfies the project constraints.[7] On reflection, the value of L1 should be zero since "...the latest start of at least one job out of the first event is zero,...this fact was automatically imposed when the value of L for the last event was set."[8]

Start events, finish events, and the quantity LS. It should be recalled that the definition of the quantity L was based on an event orientation. The expression "the latest finish of event..." was used instead of "the latest start of activity..." whenever an L value was computed or assigned. This was extremely important because at any event the value of L must equal the latest start date for only one activity beginning at that event, not for all the activities originating there. An example makes this clear. Consider the network below:



The system constraints indicate:

7. Stires and Murphy, Op.Cit., p.55.

8. Martino, Op.Cit., p.88.

Duration of Activity 4-5 = 6 time units
" " " 4-17 = 70 time units
L4 = 14 L5 = 20 L17 = 100

If activity 4-5 started at time 14, the start time at event 5 would be 14 + 6 = 20, the latest permissible. If activity 4-17 started at time 14, the start time at event 17 would be 14 + 70 = 84. This is 16 time units sooner than the latest date, 100. Obviously, then, the value of L4 is not the latest possible start date for activity 4-17.

Situations such as the above example are common in PERT networks and, as such, necessitate further consideration. First, since L is an event oriented quantity that does not necessarily pertain to all the activities originating at the event, a new quantity must be established which is activity oriented. This quantity can be designated by LS, with subscripts that relate it to a specific activity. For instance, the latest possible start of activity 4-17 would be designated as LS4-17.

Since each activity starts at an event and finishes at another event, reference can be made to the "start event" or "finish event" of an activity. Then a simple equation can be set up which relates the activity oriented quantity, LS, to the event oriented quantity, L:

$$LS_{\substack{\text{current}\\ \text{activity}}} = L_{\substack{\text{finish}\\ \text{event}}} - \text{Duration of Current Activity}$$ [9]

For example, $LS_{4-17} = L_{17}$ - Duration of Activity 4-17

$$LS_{4-17} = 100 - 70 = 30$$

Table 2 is a tabulation showing the latest start of each activity and the L values for the start and finish events for each activity of Project 1.

Summary of New Concepts

The concepts of earliest start time and latest start time and their connotations when related to events and activities were discussed. The quantities E, L, and LS were introduced. In retrospect a quantity $ES_{\substack{\text{current}\\ \text{activity}}}$, or the earliest start time of a current activity, was not discussed. There was no need to introduce such a quantity since the earliest start time for all the activities leaving an event is equal to the E value of the start event. However, consistency demands that the distinction be at least recognized. Therefore when discussing early and late starts in relation to events, the quantities E and L will be used. When discussing early and late starts with direct reference to activities, the quantities LS and ES

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9. Ibid., p.89.

ACTIVITY	DURATION	L_{start} event	L_{finish} event	LS
1-2	1.0	0	15.9	14.9
1-4	25.1	0	25.1	0
2-3	7.9	15.9	23.8	15.9
3-4	1.3	23.8	25.1	23.8
4-5	1.0	25.1	26.1	25.1
5-6	8.7	26.1	34.8	26.1

TABLE 2

LATEST START TIMES FOR ACTIVITIES OF PROJECT 1 will be used. The PERT analyst may use ES or E when relating to activities; that is strictly a personal matter. However, since the quantities LS and L are not interchangeable, it may prove confusing to interchange the early start quantities.

THE CRITICAL PATH

In the examples considered in the previous section it was noticed that at least one activity had a variation in possible starting times. Other jobs had no variation at all; the latest start time for an activity turned out to be its earliest start time as well.

"Any job that has no variation in starting time is critical, and a job with a possible variation in starting time is non-critical. The difference between the earliest starting and the latest starting time of a job, therefore, is a measure of criticality."[10]

Two situations are possible:

. The difference is not equal to zero : the activity is not critical.

. The difference is equal to zero : the activity is critical.

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10. *Ibid.*, pp.58-59.

The Critical Path of Project 1

The tabulations of Tables 1 and 2 can be integrated to show in one listing the earliest and latest starting time of the activities of Project 1; this is shown as Table 3 on the following page.

The last column of the tabulation is designated "Total Float." Total float is simply a quantitative measure of the variation in starting times for an activity.[11] Therefore:

Total Float = (Latest Start) minus (Earliest Start)

For example, the total float of activity 2-3 is 15.9 - 1.0 = 14.9.

If the total float of a job is zero, that job is critical. Hence, activities 1-4, 4-5, and 5-6 are the critical jobs of Project 1. Figure 8 portrays the network diagram for Project 1 with the critical activities connected by a thick black line, representing the critical path of the network.

"It should be clear that if any activity along the critical path is delayed the entire program will be correspondingly delayed. This is the basis for the very

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11. Miller, Op.Cit., pp.52-53.

ACTIVITY	DURATION	STARTING TIMES EARLIEST	LATEST	TOTAL FLOAT
1-2	1.0	0	14.9	14.9
1-4	25.1	0	0	0
2-3	7.9	1.0	15.9	14.9
3-4	1.3	8.9	23.8	14.9
4-5	1.0	25.1	25.1	0
5-6	8.7	26.1	26.1	0

TABLE 3

ACTIVITY DATA FOR PROJECT 1

NOTE: (1) ALL TIMES IN MINUTES
(2) THICK ARROWS REPRESENT CRITICAL ACTIVITIES

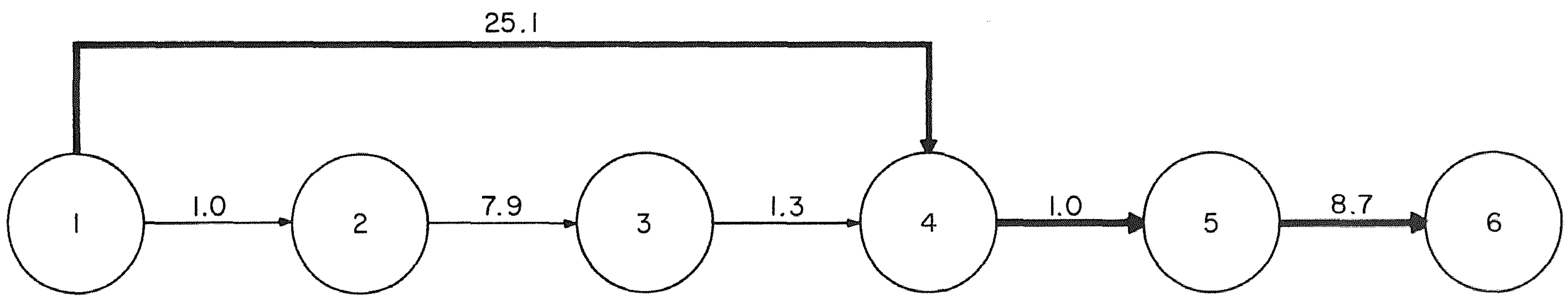

FIGURE 8

CRITICAL PATH OF PROJECT 1

important predictive feature of PERT, and represents its contribution to the principle of management by exception."[12]

Significance of Total Float and Critical Path

The calculation of the total floats and resultant designation of the critical jobs and critical path of a project give rise to the following very important PERT theorems:

- The duration of an entire project is equal to the sum of the durations along the critical path from the start to the end of a project.
- The critical path represents the longest time path through the network.
- There may possibly be more than one critical path for a project.
- No activity is critical unless it lies along a critical path.
- A delay in starting or finishing a critical activity will delay completion of the overall project by an equal amount.
- Critical activities must be given top priority in relation to resource allocation.
- If "crashing" is considered, (reducing project

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12. Ibid., p.48.

duration by heavy resource loading), the activities chosen must be critical.[13]

VARIETIES OF FLOAT IN PERT NETWORKS

Once the critical path(s) of a network has been established, an analysis of possible variations in activity starting times can result in several alternate plans, each based on the same critical path. Intrinsic to each plan are the effects of float, the allowable activity of slippage or time leeway. The four important varieties, total float, free float, independent float, and interfering float and the concept of event slack are discussed in this section.

Total Float

The total float of an activity has been defined as the excess of the time available to do a job over the time required to do the job. It is computed by subtracting the activity duration from the difference of the latest finish and earliest start times for the activity. This latter quantity is actually the maximum available time for the activity; therefore, total float should be re-defined as the excess of maximum available time over the required activity time.

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13. Martino, Op.Cit., p.102.

The definition of total float implies a starting time interrelationship among the activities of a project. "The total float of any specific activity has meaning only in relation to other jobs in the project..."[14] For example, consider the situation portrayed in Figure 9. The earliest and latest possible starting times for activities 1-2, 2-3, and 3-4 of Project 1 were plotted in all possible combinations. Using the data of Table 3 the total duration of jobs 1-2, 2-3, and 3-4 is 1.0 + 7.9 + 1.3 = 10.2 minutes, and the sum of the total floats is 14.9 + 14.9 + 14.9 = 44.7 minutes. The value of E4, the earliest start time out of event 4, is 25.1, the amount of time available to do activities 1-2, 2-3, and 3-4. Subtracting the total duration, 10.2 minutes, from the maximum available time, 25.1 minutes, yields a combined total float of 14.9 minutes for the three activities. Comparing the combined total float obtained in this manner (14.9) to that obtained by a simple summation as performed above (44.7) indicates an apparent contradiction. However, analysis of Figure 9 clarifies the situation. Float is a relative and not an absolute quantity; therefore a summation of total floats is a meaningless and erroneous manipulation. If activity 3-4 has a total float of 14.9 minutes, as shown in Situation 1, activities

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14. Ibid., p.103.

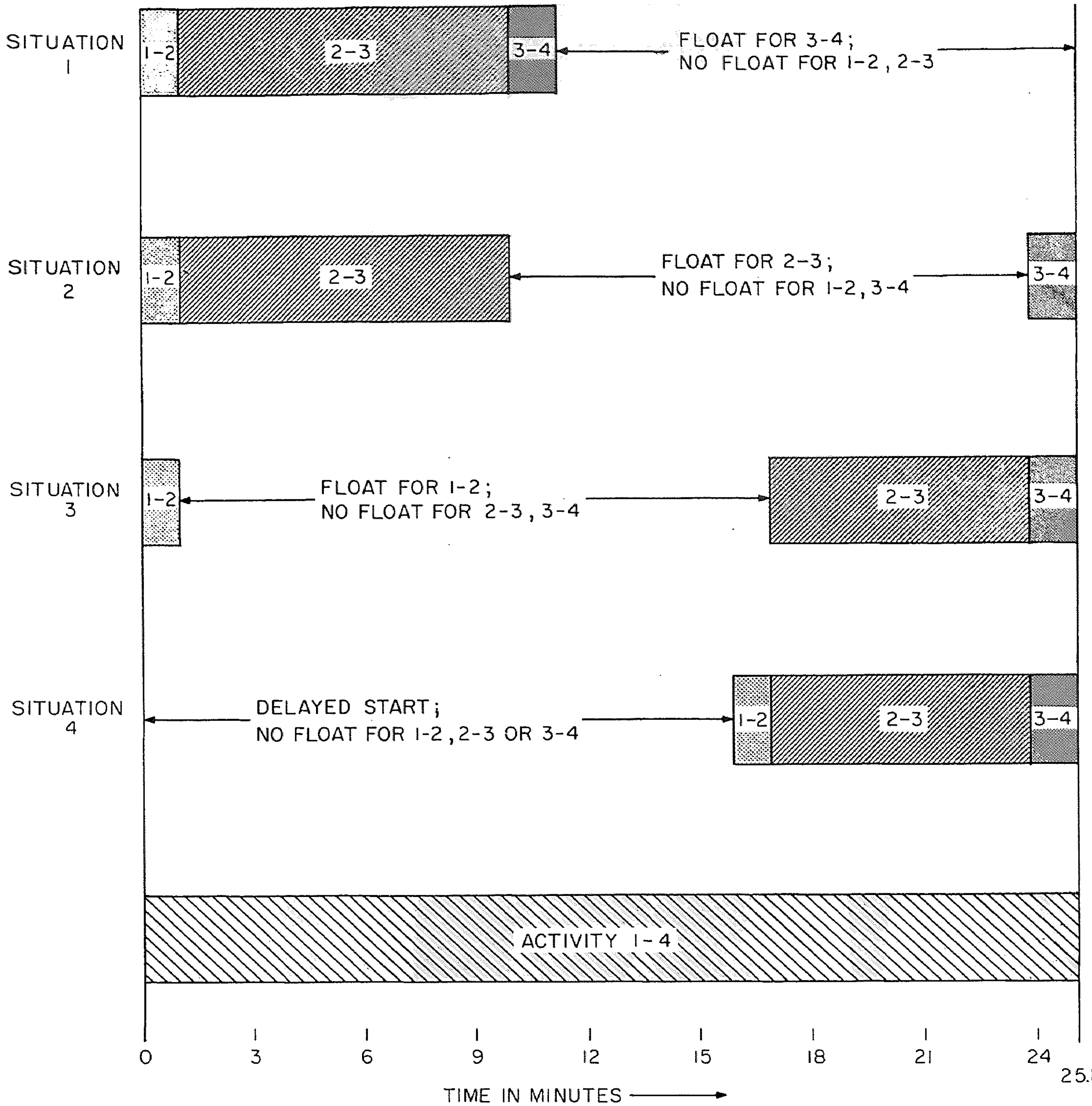

FIGURE 9

ALTERNATE SCHEDULES FOR ACTIVITIES 1-2, 2-3 AND 3-4 OF PROJECT I

1-2 and 2-3 have no float at all. If activity 1-2 has a total float of 14.9 minutes, there is no float left for activities 2-3 and 3-4, as shown in situation 3. If, for any reason whatsoever, the start of activity 1-2 is delayed until time 14.9, there would be no float at all left for the three activities. Situation 4 shows this case where the combined total float is used up before the initial job even starts.

Interference Float

The preceding discussion illustrated how a job with total float could affect or interfere with the total float of succeeding activities. A quantification of such interference could be useful to the PERT planner.

Reference to Situation 4 of Figure 9 reveals that delaying the start of activity 1-2 to its latest starting time used up all the float for activities 2-3 and 3-4. The delay introduced a downstream interference element of 14.9 minutes. Since activity 2-3 had a total float of 14.9 minutes, the interference component passed down by the late finish of activity 1-2 eliminated any time slippage previously enjoyed by activity 2-3. The same is true for activity 3-4.[15] Potential downstream interference, such as that described above, is referred to as

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15. *Ibid.*, p.104.

interference float.

Event slack. The maximum potential interference an activity can bring about can be easily calculated using the event-oriented E and L values. Consider the general activity i-j, with finish event j. The latest event start, Lj, minus the earliest event start, Ej, is the total float for at least one activity starting at event j. If several activities originated there the Lj - Ej quantity would represent the minimum valued total float for all the activities leaving event j. The maximum potential interference that activity i-j could affect here would be the use of the minimum total float; i.e., the interference float of job i-j would be equal to Lj - Ej. This data is usually available in tabulated form, similar to Table 3, and the calculation is simple. Therefore the quantity Lj - Ej is frequently used in PERT calculations and has been designated "event slack."[16]

Free Float

Another quantity of use to the planner is "free float," the allowable time slippage for an activity when all jobs start as early as possible.[17] Consider Situation 1 of Figure 9. Jobs 1-2, 2-3, and 3-4 are shown starting

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16. Miller, Op.Cit., pp.52-55.

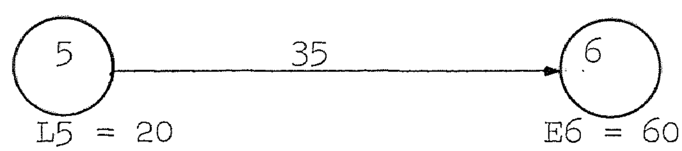
17. Martino, Op.Cit., p.106.

at their earliest possible start times; therefore job 1-2 has no float, job 2-3 has no float and job 3-4 has a float of 14.9 minutes. Or, jobs 1-2 and 2-3 have zero free float and job 3-4 has a free float of 14.9.

Independent Float

The final useful measure of activity slippage is independent float, the excess of minimum available time over the required time for an activity. The independent float of an activity measures the starting time leeway available if the preceding activities finish as late as possible and the succeeding activities start as early as possible. Unlike the situation concerning total float, an activity can be delayed up to its independent float limit without causing any downstream effect on another job.[18]

For example, consider the situation below:



The independent float for activity 5-6 is:

E6 - L5 - Duration of Activity 5-6 =

60 - 20 - 35 = 5 time units

The start of activity 5-6 could be delayed 5 time

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18. Ibid., pp.107-108.

units with no effect on the activities starting at event 6.

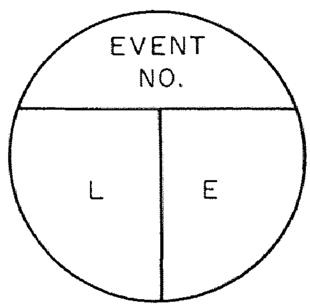
REVISED SYMBOLOGY

The basic theory and calculations of the PERT method have been presented. As each concept or computation was introduced, its relationship or contribution to the network diagram was highlighted since it is the network diagram or PERT chart with which the PERT planner and top management will be in most frequent contact. Indeed, it may be the only tangible element regarding a project that top management ever gets to see. Therefore it is imperative that the device be as informative as possible. This is not to mean that the chart should resemble a road-map; such detail could make the network ineffective. It should contain just enough to permit calculating any quantity discussed in this chapter without presenting an unpleasant, tiny lettered, cluttered appearance.

Therefore, the last network shown for Project 1, Figure 8, requires some rework to bring it up to snuff. The diagram as it stands lacks the information necessary to compute the various floats and enable the consequent setting up of alternate plans. If the E and L values were available for each event, the diagram would be complete. Hence, the following conventions are adopted and will be utilized from this point on:

An activity is represented by an arrow as above; its duration will be written in a small rectangular box, attached to the underside of the arrow (or its right side, if the arrow is vertical).

An event is represented by a circle, as below, incorporating the event number and early and late start times.



Using the symbology as standardized above, the network diagram for Project 1 has been reconstructed using the data of Tables 2 and 3 and Figure 8. This finalized PERT chart is shown as Figure 10.

NOTE: (1) ALL TIMES IN MINUTES
(2) THICK ARROWS REPRESENT CRITICAL ACTIVITIES

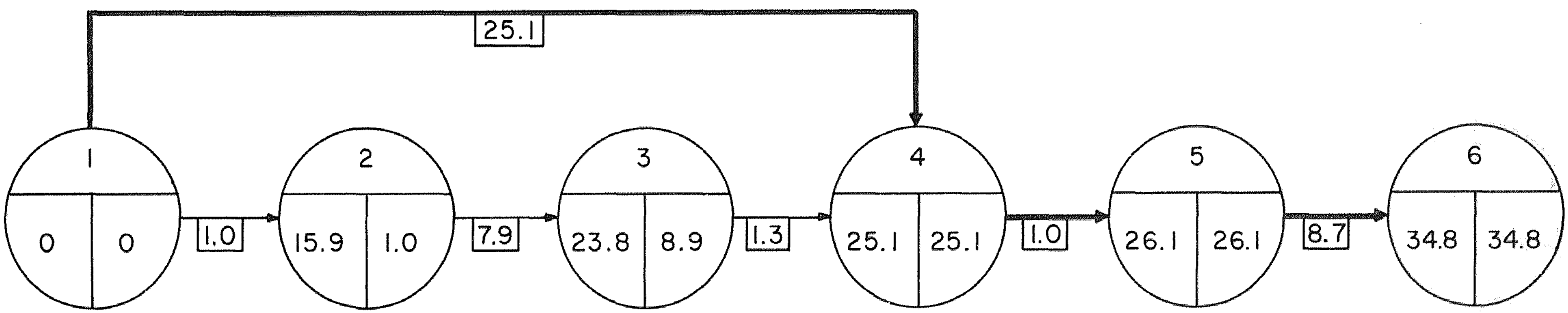


FIGURE 10

FINAL PERT NETWORK FOR PROJECT I

CHAPTER IV : PROGRAM DEFINITION

THE WRAP-AROUND SIMULATION

The preceding two chapters presented the basic philosophy and mechanics of the PERT approach to planning and scheduling. It now remains to apply this technique to the software project introduced in Chapter I. However, before a first-pass network can be constructed, the details of the project (its background, its purpose, the proposed method of attack, the system constraints, etc.) must be firmly and clearly established. Hence, a definitive exposition of the "wrap-around simulation" program is put forth in this chapter.

History of the Project

The wrap-around simulation (WAS) project was conceived as one small part of a large program to improve the availability of the Tarzan Fire Control System, or Tarzan FCS. The primary effort of the overall program was the feasibility consideration of replacing the analogue fire control computer by a DC-18 digital model. The Special Advisor to the Navy, an independent civilian organization, recommended that one DC-18 computer be installed in a shipboard Tarzan FCS for feasibility study. The performance of the DC-18 could then be observed in actual environmental conditions. However, after several roundtable discussions involving representatives from the

Naval Bureau of Weapons, the Special Advisor Company, and the SGC Company, the manufacturer of the Tarzan FCS equipment, it was agreed that a shipboard installation was unnecessary to prove out the DC-18 operational program. Further discussion led to the granting of a BuWeps contract to the SGC Company for the purpose of providing a conclusive evaluation of the operational program of the DC-18 computer in a simulated Tarzan FCS environment.[1]

Contractual Obligations

By contract, the SGC Company was responsible for the following two services:

- The provision of an operational program for the DC-06 computer, such program to simulate the "outside-world" environment in which the DC-18 would be operating as the fire control computer of the Tarzan FCS.
- The test and evaluation of the DC-18 operational program, designed by the Special Advisor Company.

The first task was to be performed at the SGC Company and at the DC-06 manufacturer's plant. Funding for travel expenses for SGC engineers to the DC-06 manufacturer location was included in the contract. The

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1. Conference with J. Morris, Sr. Engineer, SGC Co., Oct. 30, 1964.

contract further provided an allowance for the DC-06 engineer to visit SGC and lend technical assistance as required.

The second task was to be performed at the Special Advisor Company location. The DC-06:DC-18 hook-up as shown in Figure 1 was to be set up at that location so all testing was to be done there. Again, contractual provisions were made for the travel and living expenses of the visiting SGC engineers. Analysis of the test data was to be conducted back at the SGC plant.

The cost to the government for the entire SGC effort as described above was incorporated in the contract, in terms of dollars and man-months. Any overruns were to be absorbed by the SGC Company.

RESOURCE AVAILABILITY

Prior to the formation of a schedule for the project, consideration was given to the resources available to do the job.

Time

By necessity the first consideration was given to the time allotted to complete the program. The Special Advisor Company specified a program completion date of October 15, 1964; since the contract became effective the 1st of May, 1964, the SGC Company was given 5½ months to complete the entire effort.

Manpower

The assignment of personnel to the program was based on the following considerations:

. Types of occupations required. What different employees would become involved in the program? Included here might be engineering, design, production control, inspection, quality assurance, drafting, etc.

. Levels of skill, education, experience, etc. required. Standards here might include educational status, experience, attitude, and/or past performance.

. Manpower availability. Who was available for the program? Was an employee's present workload higher in priority than this project?

. Customer contact involved. Would SGC personnel be expected to meet with the customer? Which employees were best equipped to present a favorable impression to the outside world?

. Time. Is the schedule tight or is more than enough time available? The program must be staffed accordingly.

It would appear that SGC management made the personnel selection with the foregoing considerations in mind. Four SGC electrical engineers of the Tarzan Weapon Systems Group were assigned to the task; three of those engineers were of a senior level, one was of an intermediary classification. A requirement for one digital programmer from the DC-06 manufacturer was also established; again, this employee to be of a senior level. No other personnel were assigned to the program. It was to be strictly an engineering effort.

The unusually high percentage of top-level engineering personnel assigned to this program was due to three prime factors. First, the wrap-around simulation required an intense knowledge of digital techniques. A thorough understanding of the mechanizations of the analogue computer and its function in the Tarzan FCS was also necessary. Also, the ability to recognize possible system incompatibilities or equipment interface problems was essential. Secondly, extensive customer contact was anticipated. The background and experience of the senior engineer usually make him a satisfactory representative of the company, socially as well as technically. Finally, the tight schedule demanded only those employees who were capable of maximum effort under pressure, again a typical characteristic of senior level personnel.

One of the senior engineers was designated the project leader and was directed to devote half his time to this program. The other three SGC engineers were assigned to the project on a full-time basis. The senior programmer from the DC-06 company was considered part-time, his effort to consist of four weeks full-time work at the SGC plant.

Equipment

The major equipment requirements also had to be considered prior to detailed planning. It was determined that the two digital computers, the DC-06 and DC-18 and the normally used peripheral units, flexiwriter, tape units, etc., were the only major items needed. The usual electrical test equipment such as Tektronix scopes, Simpson or Weston Multimeters, vacuum tube voltmeters, etc. would, of course, be required but it was felt that procurement of such ancillary equipment would present no problems.

As previously stated, the digital computers and associated peripheral equipment were to be located at the Special Advisor Company and all tests were to be conducted at that site. It was the responsibility of the Special Advisor to see that the necessary intra-computer cabling was installed.

Therefore, all the required major equipments were to be available at the Special Advisor Company and all the necessary preparations prior to test and checkout by SGC engineers were to be made.

THE SGC PLAN AND SCHEDULE

The working plan and schedule for the WAS project was set up by the four SGC engineers themselves. Their approach consisted of breaking down the program into its basic activities, assigning those activities amongst themselves, and establishing a schedule and milestone chart based on the sub-projects of the overall project.

Activity Breakdown

The planning function as performed by the four engineers culminated in a list of responsibilities for each of the three full-time men. The project leader was to assist any of the other three; hence, no specific list was constructed for him. Tables 4, 5, and 6 present the specified individual levels of responsibility.

The WAS Schedule and Milestone Chart

Having spelled out each man's workload, the engineers utilized that information to set up a schedule-milestone chart, shown by Figure 11. The document was a somewhat simplified Gantt Chart and as such became the control mechanism for the program.[2] Characteristic of a

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2. See Wallace Clark, The Gantt Chart, Sir Isaac Pitman and Sons, London, 1942, for a complete discussion on the Gantt Chart and its application.

1. Detailed flow charts for DC-06 simulation system.
2. Simulation documentation.
3. Computation of real time estimates for DC-06 for various modes.
4. Knowledge of peripheral equipment.
5. Methods of data collection, presentation, and reduction for DC-06:DC-18 setup.
6. DC-06 program cycling.
7. Provision of program changes.
8. Knowledge of Input/Output hook-up, coordination, and timing of DC-06:DC-18 loop.
9. Compatibility of different word lengths.
10. General operating knowledge of both digital computers.
11. Knowledge of Input/Output hook-up, coordination, and timing of DC-18 using actual conversion gear.
12. Knowledge of test setup as installed at Special Advisor Company.

TABLE 4[3]

RESPONSIBILITIES OF SGC ENGINEER NO. 1

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3. John Fare, Unpublished Notes on WAS Project, May, 1964.

1. Descriptions and diagrams of functional modes of analogue computer.
2. Preparation of Input/Outputs for each functional mode of DC-18.
3. Preparation of external signal required by DC-18 Input/Output control words.
4. Preparation of DC-06:DC-18 Input/Output formats.
5. Consideration of multiple programs of different content and scope.
6. Establish guidance system requirements.
7. Preparation of Guidance Radar simulation.
8. Preparation of missile simulation.
9. Preparation of simulated coast mode.
10. Assistance in flow chart preparation.
11. Knowledge of DC-06 and DC-18 programming techniques.

TABLE 5[4]

RESPONSIBILITIES OF SGC ENGINEER NO. 2

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4. *Ibid.*

1. Generation of all DC-06 and DC-18 system equations.
2. Assistance in mechanizations.
3. Assistance in analog or digital system analysis.
4. Provision of error analysis.
5. Provision of DC-06 fixed point and scaling.
6. Knowledge of DC-18 fixed point and scaling.
7. Generation of all test problems and real time numerical solutions.
8. Consideration of input noise and its simulation.
9. Consideration of depth of testing required to check out DC-18.
10. Provision of DC-06 internal debugging circuit designs.
11. Provision of alternate system capabilities based on the digital replacement.
12. Assistance in simulation of real-world environment.

TABLE 6[5]

RESPONSIBILITIES OF SGC ENGINEER NO. 3

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5. Ibid.

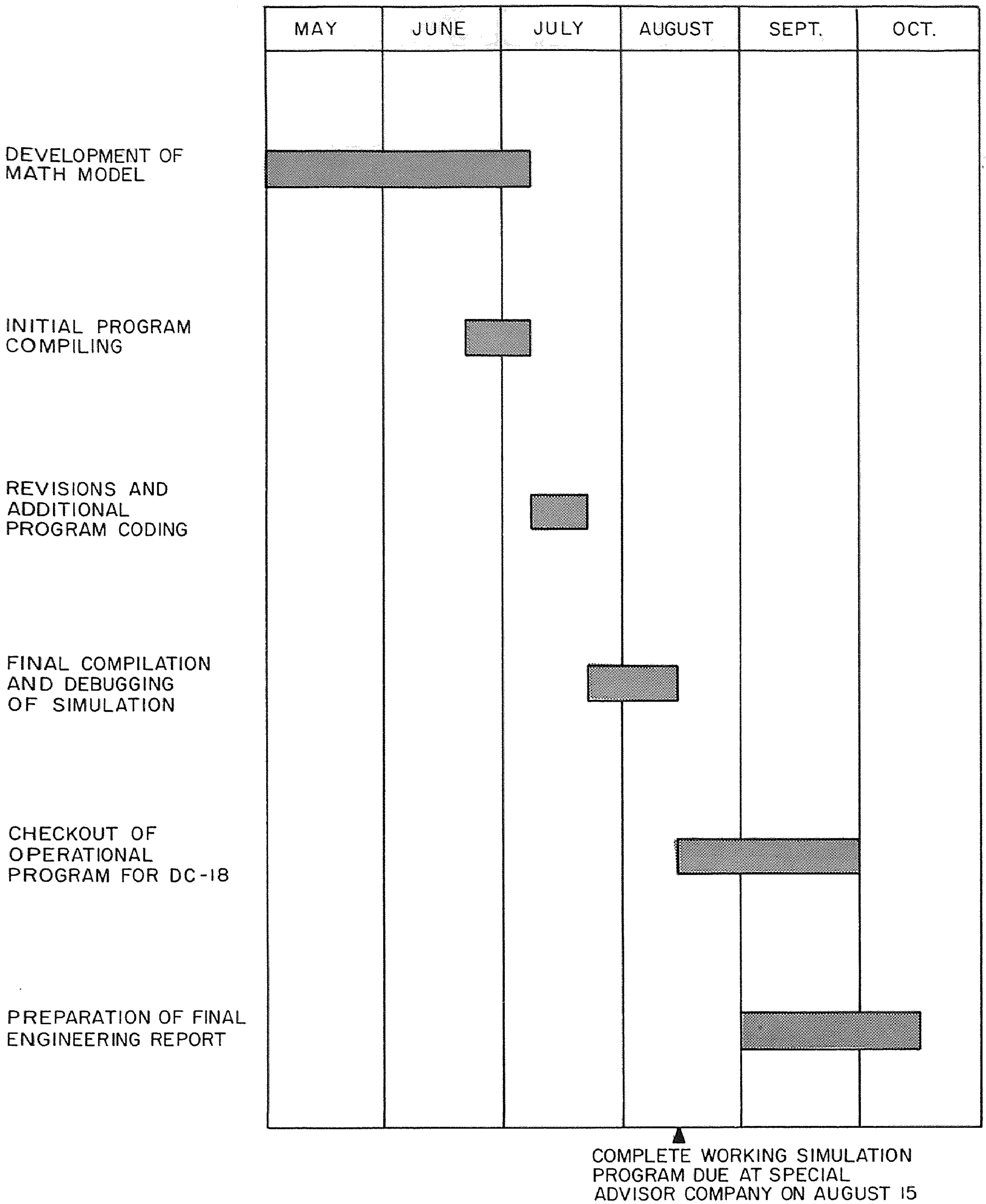

FIGURE 11

SGC SCHEDULE AND MILESTONE CHART

Gantt Chart, the SGC chart does not specify loading or other system constraints upon the starts and completions of the individual activities.[6] However this was the device used and the attempt was made to comply with it as closely as possible.

Plan vs. actual. Tables 4, 5, and 6 and Figure 11 constitute the "plan" by which the WAS project was run. Up to August 15 the schedule-milestone chart was tightly adhered to; the DC-06 simulation was ready for use at the Special Advisor Company. However, from that point on the chart was no longer an accurate representation of the actual effort. The entire month of September was spent eliminating interface problems caused by DC-06:DC-18 incompatibilities. Therefore, at the suggestion of the Special Advisor Company, six more man-months were added to the original effort. In an attempt to make up lost time the DC-18 operational program checkout became an overtime activity and the schedule-milestone chart was of no further use. The program was finally completed with an estimated time overrun of 30% and a cost overrun of about 10%. The general impression was that the WAS project was a successful effort on the part of SGC.

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6. Miller, Op.Cit., p.6.

CHAPTER V : PERTING THE WAS PROJECT

Even though the SGC Company overran the cost and time estimates during the WAS Project, the Naval Bureau of Weapons and the Special Advisor Company were very well satisfied with the final outcome. There were two reasons for this:

1. The SGC effort was a fine technical achievement. Each of the four SGC employees are extremely competent engineers and their combined performance on the WAS Project resulted in a technically excellent engineering effort.

2. The overruns were buried in the funding of new contracts which covered many different items.

The good feeling fostered by the top-flight technical results was in no way dampened by the overruns which were absorbed by some other contract. Admittedly, the program was a technical success. But it was not a financial one. Considering the Gantt-type schedule employed, with its inherent shortcomings, one is not really surprised at the outcome.

Could the project have been planned and scheduled in greater depth? Could it have responded favorably to a rigorous method like PERT? Such questions are worth consideration.

In this chapter the PERT method is applied to the soft-ware program, the WAS Project.

ACTIVITIES : WAS PROJECT

In setting up their individual levels of responsibility, as enumerated in Tables 4, 5, and 6 of the last chapter, the SGC engineers were actually breaking down the project into its basic activities. Using those lists as a guide this writer generated a tabulation of activities required to accomplish the WAS Project.

Correlation of Responsibilities to Activities

The activities for the project are tabulated in Table 7. Except for some minor wording changes, the list of Table 7 is simply a merging of the three responsibility lists. This writer might have generated a slightly different list had he undertaken the problem on his own. However, since those lists represent the original planning by which the SGC effort was managed it was decided to utilize them as closely as possible.

In order to convert from responsibility to activity some rewording and rephrasing were necessary. For example, the responsibility "Knowledge of DC-06 programming techniques" converted to the activity "Acquire knowledge of DC-06 programming techniques." Likewise, the responsibility "DC-06 program cycling" became the

1. Prepare flow charts for DC-06 simulation system.
2. Prepare simulation documentation.
3. Verify the procurement and accessibility of peripheral equipment.
4. Establish and prescribe methods of date collection, presentation, and reduction for DC-06 : DC-18 setup.
5. Prescribe the DC-06 program cycling.
6. Prepare the means for program changes and data input.
7. Acquire the knowledge of the Input/Output hook-up, coordination, and timing of the DC-06 : DC-18 loop.
8. Establish a compatibility among different word lengths.
9. Acquire general operating knowledge of DC-06 computer.
10. Acquire the knowledge of the Input/Output hook-up, coordination, and timing of DC-18 using actual conversion gear.
11. Acquire the knowledge of test setup as installed at Special Advisor Company.
12. Prepare functional diagrams of analogue computer operating modes as applied to DC-18.
13. Prepare Input/Outputs for each functional mode of DC-18.
14. Prescribe the external signal required by the DC-18 Input/Output control words.
15. Prepare DC-06 : DC-18 Input/Output formats.

TABLE 7 : ACTIVITIES OF WAS PROJECT

16. Establish guidance system requirements.
17. Prepare guidance radar simulation.
18. Prepare missile simulation.
19. Prepare coast mode simulation.
20. Acquire knowledge of DC-06 programming techniques.
21. Generate all DC-06 system equations.
22. Prepare error analyses.
23. Prepare DC-06 fixed point and scaling.
24. Generate all test problems and real time numerical solutions.
25. Prepare noise simulations.
26. Design DC-06 internal self-checks.
27. Prepare the program coding.
28. Debug the program coding.
29. Acquire the general operating knowledge of the DC-18 computer.
30. Acquire the knowledge of DC-18 programming techniques.
31. Test the DC-06 : DC-18 closed loop system.

TABLE 7 (cont.)

activity "Prescribe the DC-06 program cycling." In that manner the activity breakdown of Table 7 was generated.

Predecessor - Successor Relationships

In order to establish the predecessor - successor relationships for each activity the WAS Project was broken down into the following six sub-projects:

. Functional operation of analogue computer

. Theory and operation of DC-18 computer

. DC-06 simulation

. Testing of DC-06 : DC-18 system

. Error analyses

. Documentation : Final Engineering Report

The inter-dependence of the sub-projects was then established in block diagram form, as shown in Figure 12.

Sub-project activities. The activities of the over-all program were categorized in terms of the sub-projects to which they applied. For example, Activity No. 27 from Table 7, "Prepare the program coding," was classified in the sub-project "DC-06 Simulation." And Activity No. 2, "Prepare Simulation Documentation," was categorized in sub-project "Final Engineering Report." Figure 13 is a modification of Figure 12 which illustrates the activity classification for the entire project and the predecessor-successor relationships for the six groups of activities.

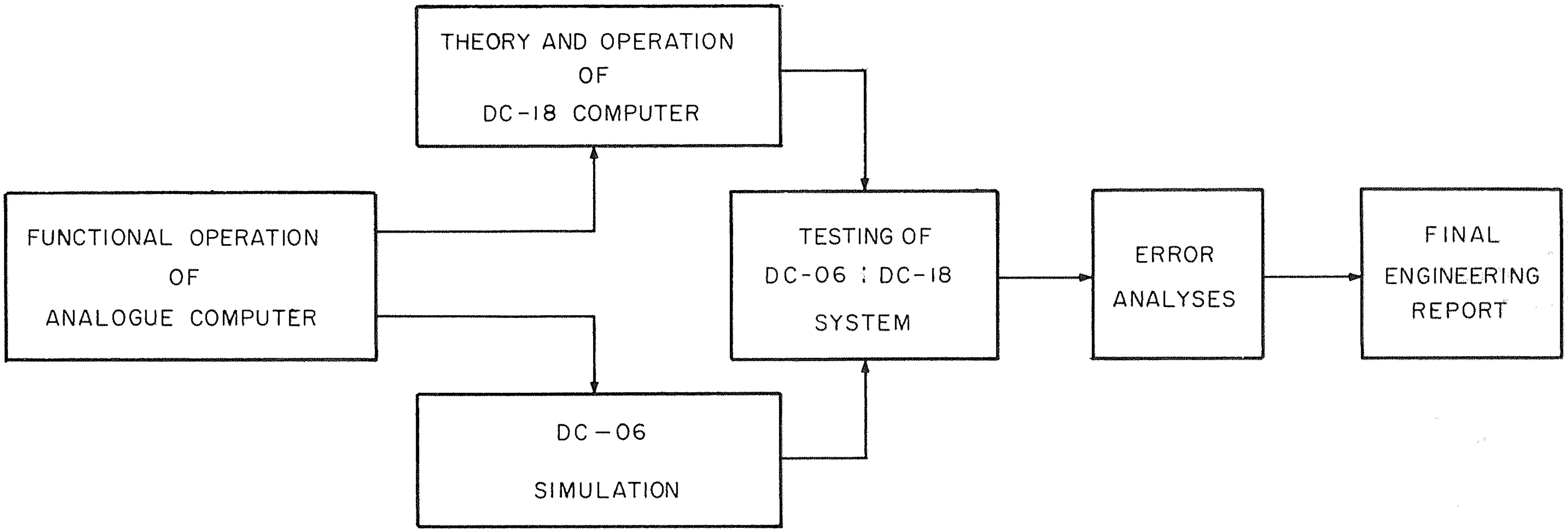


FIGURE 12
SUB-PROJECT INFORMATION FLOW

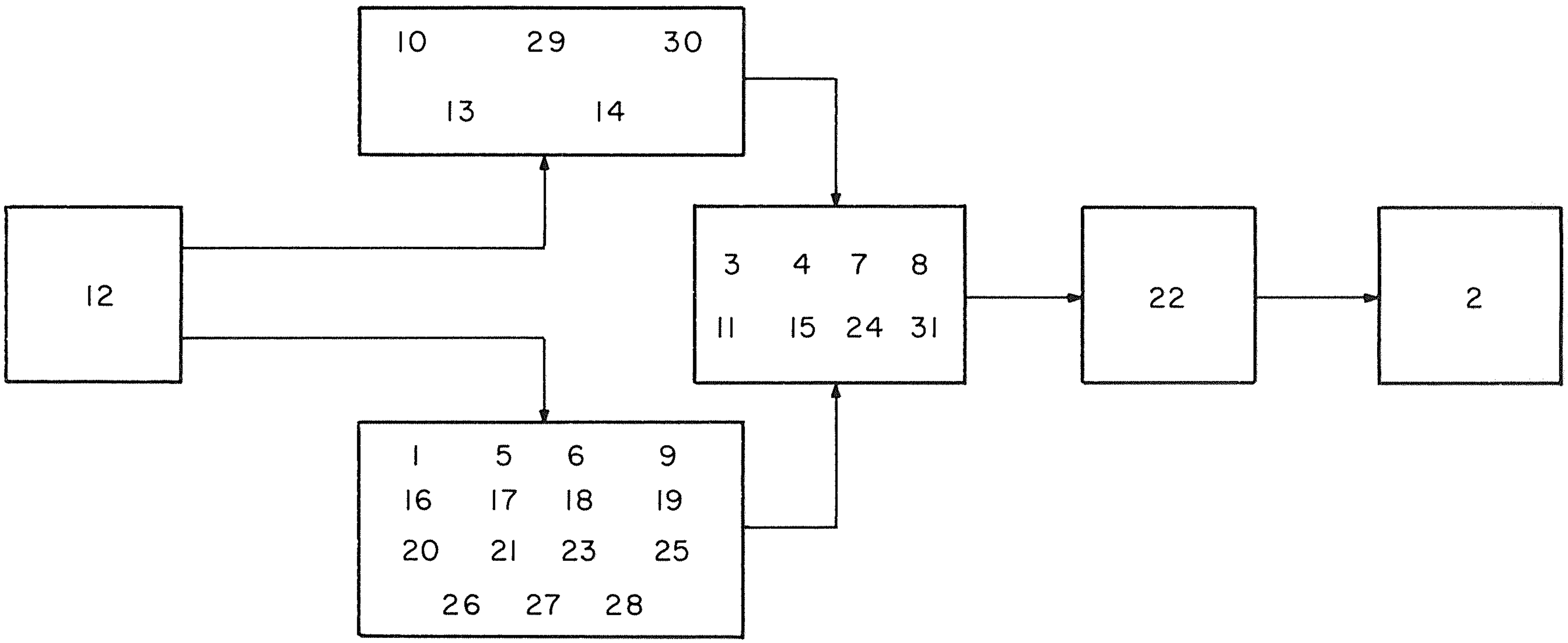
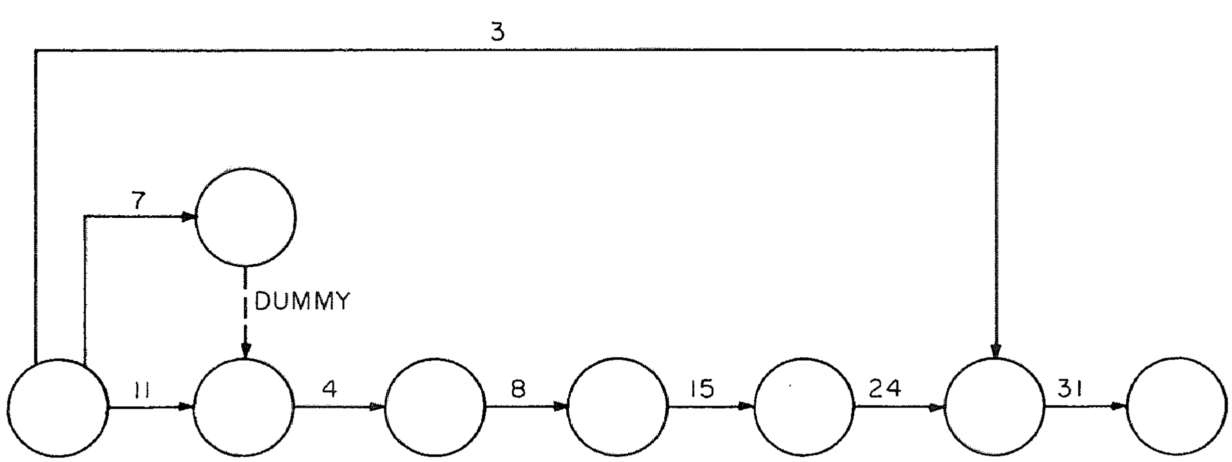


FIGURE 13
ACTIVITY CLASSIFICATION

For the present the activities are referred to by the numbers assigned them in the list of Table 7. This is for the sake of convenience only. Eventually each activity will be described relative to its start and finish event numbers. However in the absence of such information it is not incorrect at this point to refer to an activity by a single number.

<u>Sub-project arrow diagrams</u>. Dividing the WAS Project into six sub-projects permitted the generation of an overall arrow diagram by an integration of six separate sub-networks. Each group of activities was considered independently and an arrow diagram representing its activity interrelationships was set up. For example, the network for the sub-project "Testing of DC-06 : DC-18 System" was set up as shown below:

Note: Numbers identify activities



The next step in the development of the overall network diagram was to establish common junction points which tied the six sub-networks together. Figures 12 and 13 proved to be the sole reference here. An interface point must exist between sub-projects "DC-06 Simulation" and "Testing of DC-06 : DC-18 System;" therefore, the first arrow of the latter must be preceded by the last arrow of the former. In the case of parallel paths, such as the sub-projects "Theory and Operation of DC-18 Computer" and "DC-06 Simulation" the start and finish points must coincide. Hence, relating the six sub-networks to conform with the block diagrams of Figures 12 and 13 produced the first-pass arrow diagram for the WAS Project as shown in Figure 14. In that network, again, activities were represented by numbers with the number zero (0) used to refer to any dummy activity.

EVENTS : WAS PROJECT

Once the activity oriented first-pass network was established, the events of the project were described and identified. The description of each event was derived from the activities which terminated at that event. For example, the event terminating the activity "Prepare flow charts for DC-06 simulation system," activity 1 of Figure 14, was described as "DC-06 simulation flow charts prepared." And the interface event terminating the activi-

NOTE: (1) NUMBERS REPRESENT ACTIVITIES
(2) ZERO (0) REPRESENTS A DUMMY ACTIVITY

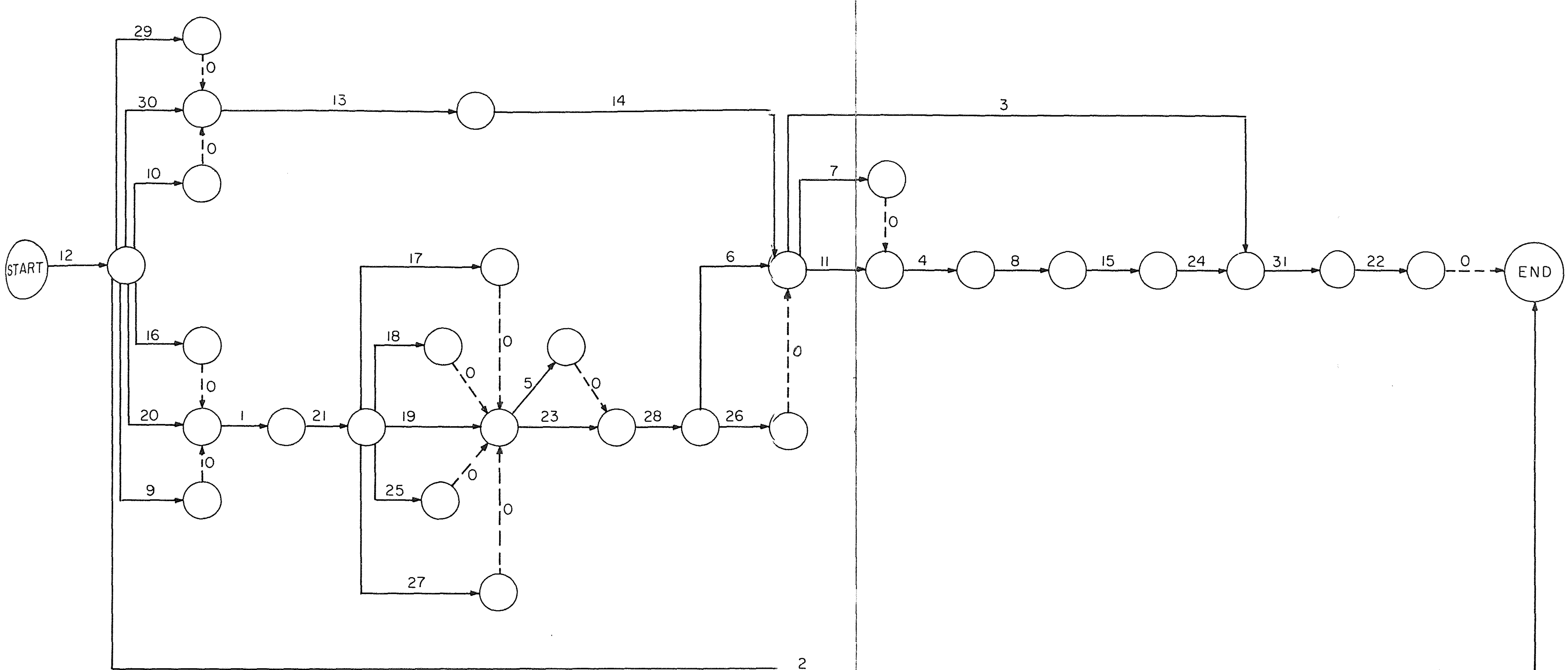


FIGURE 14
FIRST PASS NETWORK: WAS PROJECT

ties 6 and 14 of Figure 14 was described as "DC-06 Simulation prepared : Complete knowledge of DC-18 Acquired."

Event and Activity Dictionaries

The events were then identified by number, as suggested in Chapter 2, and an event dictionary was established. Once the events were identified by numbers it was no longer necessary to refer to the activities by number; the activities could then be identified by their predecessor and successor event numbers, the conventional PERT approach. An activity dictionary was then tabulated on the same sheet as the event dictionary and both are shown on the pull-out Table 8. It was decided to employ a pull-out chart rather than several sheets of standard sized paper because of the ease with which the PERT analyst could relate events to activities and the dictionaries to the PERT chart. Two large sheets of paper which can be spread out on a small desk are much more desirable than a stack of pages which requires considerable cross-reference.

Numbering of events. The assignment of event numbers was done on an arbitrary though orderly basis. The events were numbered in ascending order from left to right; if the first-pass network showed a column of events, those events were numbered in ascending order from top to bottom. For the relatively simple and

Event Dictionary

1. Start of project
2. Capability of analogue computer defined
3. General operating knowledge of DC-18 acquired
4. Knowledge of DC-18 programming techniques acquired
5. Knowledge of DC-18 I/O environmental hook-up acquired
6. Guidance system requirements specified
7. Knowledge of DC-06 programming techniques acquired
8. General operating knowledge of DC-06 acquired
9. DC-06 simulation flow charts prepared
10. DC-18 Input/Outputs prepared
11. DC-06 system equations prepared
12. Guidance radar simulation prepared
13. Missile simulation prepared
14. Coast mode simulation prepared
15. Noise simulations prepared
16. Program coding prepared
17. DC-06 program cycling specified
18. DC-06 fixed point and scaling prepared
19. Program coding O.K.
20. DC-06 simulation prepared : Complete knowledge of DC-18 acquired
21. DC-06 self checks established
22. Knowledge of DC-18 : DC-06 I/O hook-up acquired
23. Knowledge of Special Advisor Company test setup acquired
24. Methods of data collection, presentation, and reduction specified
25. Word length compatibility established
26. DC-06 : DC-18 I/O formats prepared
27. All equipment on hand : Test plans specified
28. Testing complete
29. Error analyses complete
30. End of project

Activity Dictionary

- 1-2. Prepare functional diagrams of analogue computer operating modes as applied to DC-18
- 2-3. Acquire the general operating knowledge of the DC-18 computer
- 2-4. Acquire the knowledge of DC-18 programming techniques
- 2-5. Acquire the knowledge of the I/O hook-up, coordination, and timing of DC-18 using actual conversion gear
- 2-6. Establish guidance system requirements
- 2-7. Acquire knowledge of DC-06 programming techniques
- 2-8. Acquire general operating knowledge of DC-06
- 2-30. Prepare simulation documentation
- 3-4. Dummy
- 4-10. Prepare Input/Outputs for each functional mode of DC-18
- 5-4. Dummy
- 6-7. Dummy
- 7-9. Prepare flow charts for DC-06 simulation system
- 8-7. Dummy
- 9-11. Generate all DC-06 system equations
- 10-20. Prescribe external signal required by the DC-18 I/O control words
- 11-12. Prepare guidance radar simulation
- 11-13. Prepare missile simulation
- 11-14. Prepare coast mode simulation
- 11-15. Prepare noise simulations
- 11-16. Prepare the program coding
- 12-14. Dummy
- 13-14. Dummy
- 14-17. Prescribe the DC-06 program cycling
- 14-18. Prepare DC-06 fixed point and scaling
- 15-14. Dummy
- 16-14. Dummy
- 17-18. Dummy
- 18-19. Debug the program coding
- 19-20. Prepare the means for program changes and data input
- 19-21. Design DC-06 internal self-checks
- 20-22. Acquire the knowledge of the I/O hook-up, coordination, and timing of the DC-06 : DC-18 loop
- 20-23. Acquire the knowledge of test setup as installed at Special Advisor Company
- 20-27. Verify the procurement and accessibility of peripheral equipment
- 21-20. Dummy
- 22-23. Dummy
- 23-24. Establish and prescribe methods of data collection, presentation, and reduction for DC-06 : DC-18 setup
- 24-25. Establish a compatibility among different word lengths
- 25-26. Prepare DC-06 : DC-18 Input/Output formats
- 26-27. Generate all test problems and real time numerical solutions
- 27-28. Test the DC-06 : DC-18 closed loop system
- 28-29. Prepare error analyses
- 29-30. Dummy

TABLE 8.

uncomplicated network considered here an arbitrary assignment of event numbers introduced no confusion. However, in a more complex system involving 100 or more events a more rigid approach would be desirable. R. L. Martino devoted an entire chapter of his most excellent book "Finding the Critical Path" to a presentation of a systematic, logical method of event number assignment. Such a method is recommended by this writer for very large networks.

ACTIVITY TIME ESTIMATES

For the acquisition of the time estimates for the WAS Project activities the following ground rules were established:

- The time estimates would be obtained from the SGC engineers who worked on the project.
- The estimates would be predicated on the original program planning, not on the actual performance.
- The estimates would refer to four (4) engineers working an eight hour day, five day week.
- An estimate would reflect the time required to accomplish one specific activity only.

Source of Estimates

The source of the most likely time estimates for all the WAS Project activities was one of the SGC senior engineers who worked full time on the program. The optimistic and pessimistic estimates were made up by this writer based on information afforded by the SGC senior engineer.

The decision to utilize only one of the three SGC engineers for time estimating was based on several considerations. First, since the estimates were to be secured after the fact it was recognized that an unusual source of bias was to be reckoned with. The durations were to be estimated with full knowledge of the actual values. It is not unreasonable to assume that such an awareness must influence an estimator to some degree. Therefore, rather than procure estimates from three different sources and introduce varying levels of bias only one source was utilized in the hope that a somewhat constant biasing effect could be realized.

The second consideration was given to the knowledge of and familiarity with the activities themselves. The SGC engineer selected to make the estimates had a complete knowledge of every activity of the WAS Project. He therefore qualified to estimate not only his own assigned activities but all others as well.

The third and final consideration was a technical and character appraisal of the senior engineer, himself.

As already mentioned the man is extremely competent technically and well qualified to handle the job from that angle. From the standpoint of dealing with the unordinary bias previously discussed in this section the man is equally up to the task. Therefore he was considered to be the most reliable source of most likely estimates.

The optimistic and pessimistic estimates were generated by this writer in collaboration with the SGC senior engineer mentioned above. Since that engineer's knowledge of the PERT technique was somewhat limited it was decided that this writer would design the optimistic and pessimistic times on the basis of a question and answer interview with the senior engineer. This method worked out quite well. The three time estimates for each WAS Project activity are tabulated in Table 9, along with the expected time durations, te, calculated as described in Chapter II, page 47.

Second Pass Network : WAS Project

At this point, a second pass network was constructed which incorporated the event numbers and expected activity time durations. With the entrance of this chart the temporary device of activity numbering was discontinued since activity identification by predecessor and successor event numbers was then made possible. This net-

Activity	to	tm	tp	te
1-2	1	3	10	3.8
2-3	8	10	14	10.3
2-4	10	12	15	12.2
2-5	10	12	14	10.0
2-6	20	40	70	41.7
2-7	10	12	15	12.2
2-8	8	10	14	10.3
2-30	60	75	90	75.0
3-4	0	0	0	0.0
4-10	3	5	10	5.5
5-4	0	0	0	0.0
6-7	0	0	0	0.0
7-9	12	15	25	16.2
8-7	0	0	0	0.0
9-11	12	15	20	15.3
10-20	3	5	8	5.2
11-12	10	20	40	21.7
11-13	5	30	60	30.8
11-14	12	15	25	16.1
11-15	0	0	0	0.0
11-16	30	50	100	55.0
12-14	0	0	0	0.0
13-14	0	0	0	0.0

Activity	to	tm	tp	te
14-17	7	10	13	10.00
14-18	17	20	30	21.1
15-14	0	0	0	0.0
16-14	0	0	0	0.0
17-18	0	0	0	0.0
18-19	1	30	60	30.1
19-20	10	20	45	22.5
19-21	20	25	35	25.8
20-22	18	20	22	20.0
20-23	3	5	7	5.0
20-27	1	5	10	5.2
21-20	0	0	0	0.0
22-23	0	0	0	0.0
23-24	10	20	35	20.8
24-25	4	5	6	5.0
25-26	12	20	35	21.1
26-27	15	20	50	24.1
27-28	14	25	60	29.0
28-29	16	20	30	21.0
29-30	0	0	0	0.0

Note: All estimates in man-days

TABLE 9

WAS PROJECT ACTIVITY TIME ESTIMATES

work is shown in Figure 15.

GENERATION OF CRITICAL PATH

The critical path of the WAS Project PERT network was developed in accord with the philosophy outlined in Chapter III. The E and L values of the events and the earliest and latest start times and total floats for each activity were calculated and tabulated in Tables 10 and 11. The mechanics leading to the tabulations were similar to those detailed in Chapter III and compiled in the listing of Table 3.

Critical Path : WAS Project

In the tabulation of Table 11 the activities whose total floats are zero were marked by asterisks. Those are the critical activities of the WAS Project. Based on that information and the event data of Table 10 a third and final PERT network was constructed showing the critical path, event nomenclature, and activity durations in accord with the symbology adopted at the end of Chapter III. Therefore, Figure 16 represents the finalized PERT schedule for the WAS Project.

Impact of the final PERT network. The PERT chart shown in Figure 16 has two highly significant features to offer WAS Project management. First it was constructed so that the critical activities lie on a straight line

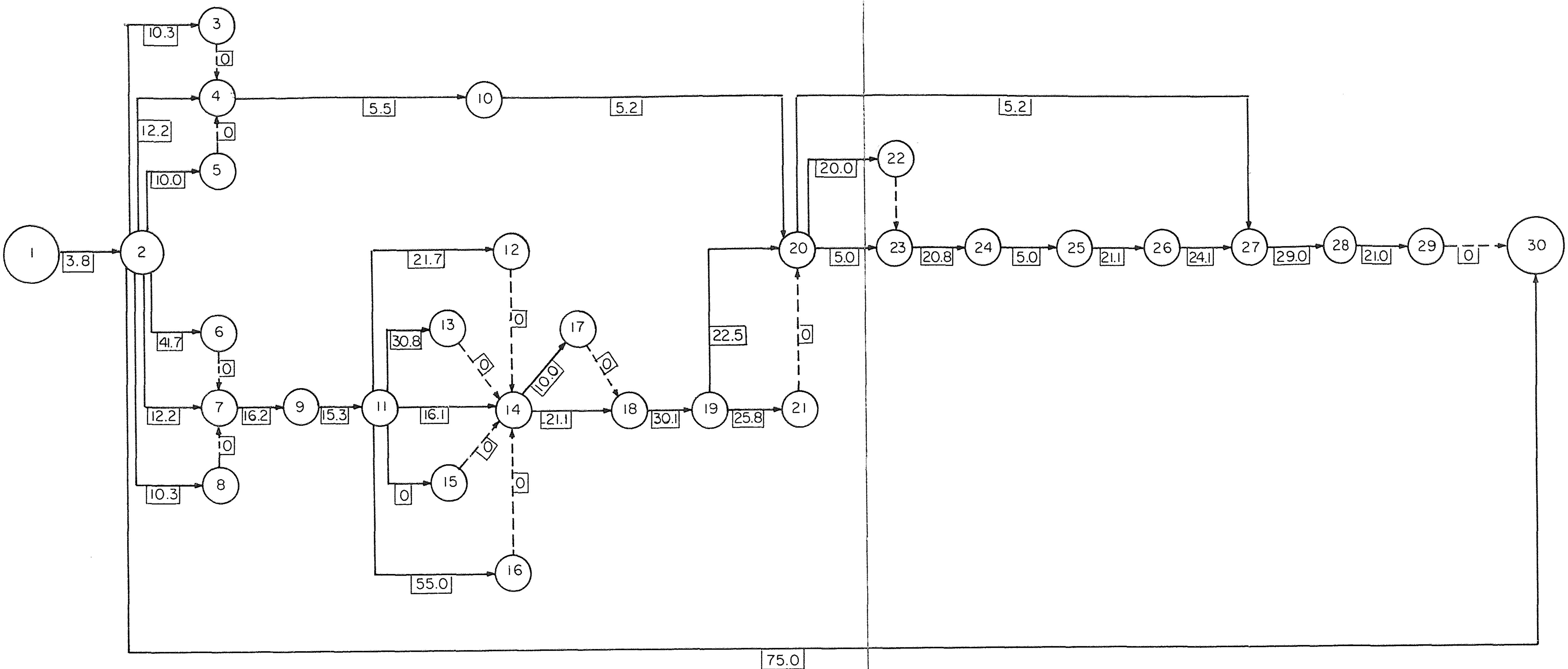


FIGURE 15

SECOND PASS NETWORK: WAS PROJECT

Event	E	L
1	0.0	0.0
2	3.8	3.8
3	14.1	198.3
4	16.0	198.3
5	13.8	198.3
6	45.5	45.5
7	45.5	45.5
8	14.1	45.5
9	61.7	61.7
10	21.5	203.8
11	77.0	77.0
12	98.7	132.0
13	107.8	132.0
14	132.0	132.0
15	77.0	132.0
16	132.0	132.0
17	142.0	153.1
18	153.1	153.1
19	183.2	183.2
20	209.0	209.0
21	209.0	209.0
22	229.0	229.0
23	229.0	229.0
24	249.8	249.8
25	254.8	254.8
26	275.9	275.9
27	300.0	300.0
28	329.0	329.0
29	350.0	350.0
30	350.0	350.0

TABLE 10

EVENT DATA : WAS PROJECT

Activity	Duration	Starting Times Earliest	Latest	Total Float
* 1-2	3.8	0.0	0.0	0.0
2-3	10.3	3.8	188.0	184.2
2-4	12.2	3.8	186.1	182.3
2-5	10.0	3.8	188.3	184.5
* 2-6	41.7	3.8	3.8	0.0
2-7	12.2	3.8	33.3	29.5
2-8	10.3	3.8	35.2	31.4
2-30	75.0	3.8	275.0	271.2
3-4	0.0	14.1	198.3	184.0
4-10	5.5	16.0	198.3	182.3
5-4	0.0	13.8	198.3	184.5
* 6-7	0.0	45.5	45.5	0.0
* 7-9	16.2	45.5	45.5	0.0
8-7	0.0	14.1	45.5	31.4
* 9-11	15.3	61.7	61.7	0.0
10-20	5.2	21.5	203.8	182.3
11-12	21.7	77.0	110.3	33.3
11-13	30.8	77.0	101.2	24.2
11-14	16.1	77.0	115.9	38.9
11-15	0.0	77.0	132.0	55.0
* 11-16	55.0	77.0	77.0	0.0
12-14	0.0	98.7	132.0	33.3
13-14	0.0	107.8	132.0	24.2
14-17	10.0	132.0	143.1	11.1

TABLE 11

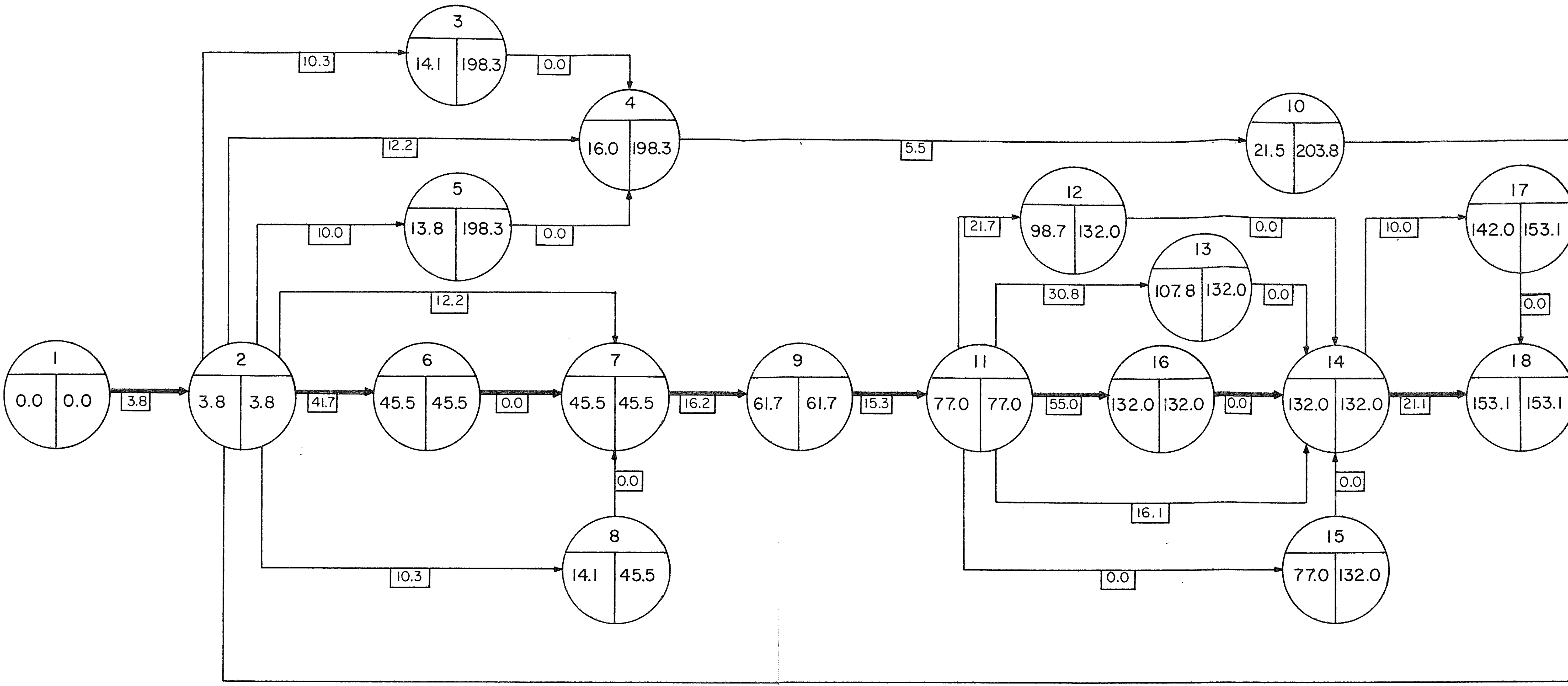
ACTIVITY DATA : WAS PROJECT

Activity	Duration	Starting Times Earliest	Latest	Total Float
* 14-18	21.1	132.0	132.0	0.0
15-14	0.0	77.0	132.0	55.0
* 16-14	0.0	132.0	132.0	0.0
17-18	0.0	142.0	153.1	11.1
* 18-19	30.1	153.1	153.1	0.0
19-20	22.5	183.2	186.5	3.3
* 19-21	25.8	183.2	183.2	0.0
* 20-22	20.0	209.0	209.0	0.0
20-23	5.0	209.0	224.0	15.0
20-27	5.2	209.0	294.8	85.8
* 21-20	0.0	209.0	209.0	0.0
* 22-23	0.0	229.0	229.0	0.0
* 23-24	20.8	229.0	229.0	0.0
* 24-25	5.0	249.8	249.8	0.0
* 25-26	21.1	254.8	254.8	0.0
* 26-27	24.1	275.9	275.9	0.0
* 27-28	29.0	300.0	300.0	0.0
* 28-29	21.0	329.0	329.0	0.0
* 29-30	0.0	350.0	350.0	0.0

Note: Activities marked with asterisk are critical

TABLE 11 (cont.)

ACTIVITY DATA : WAS PROJECT


1
0.0
0.0
3.8
2
3.8
3.8
10.3
3
14.1
198.3
0.0
12.2
4
16.0
198.3
5.5
10
21.5
203.8
10.0
5
13.8
198.3
0.0
12.2
41.7
6
45.5
45.5
0.0
7
45.5
45.5
0.0
8
14.1
45.5
10.3
16.2
9
61.7
61.7
15.3
11
77.0
77.0
21.7
12
98.7
132.0
0.0
30.8
13
107.8
132.0
0.0
55.0
16
132.0
132.0
0.0
14
132.0
132.0
16.1
0.0
15
77.0
132.0
0.0
10.0
17
142.0
153.1
0.0
21.1
18
153.1
153.1

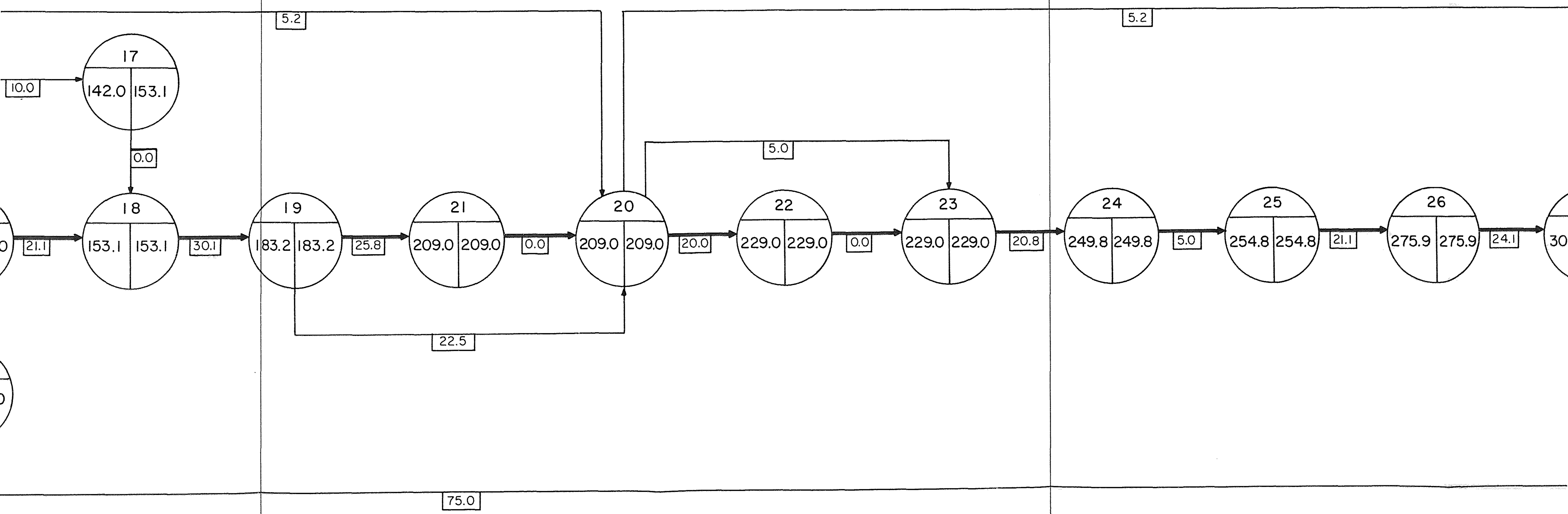
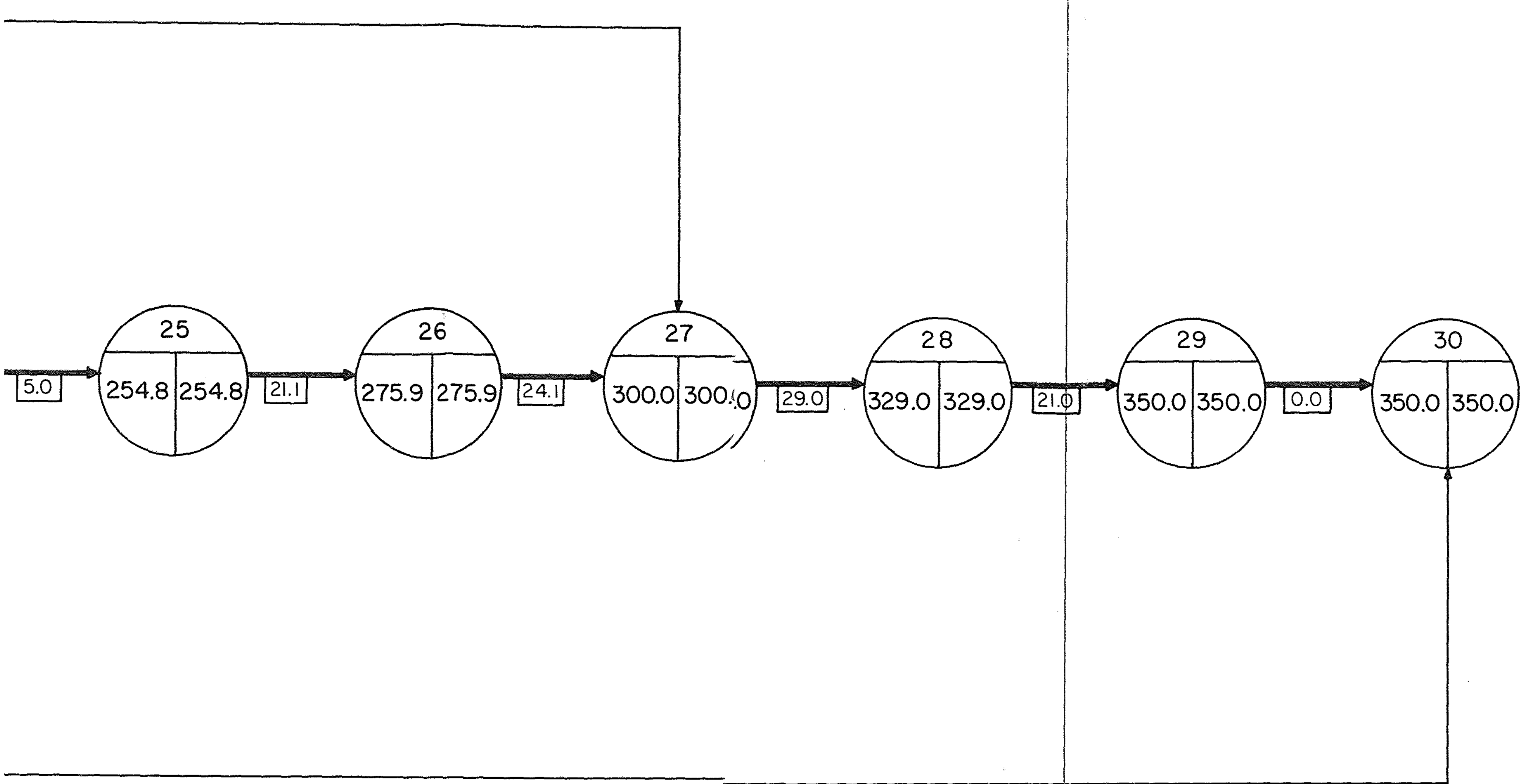


FIGURE 16

FINAL PERT NETWORK : WAS PROJECT



5.0
25
254.8
254.8
21.1
26
275.9
275.9
24.1
27
300.0
300.0
29.0
28
329.0
329.0
21.0
29
350.0
350.0
0.0
30
350.0
350.0

(the critical path) from left to right along the centerline of the chart. In this way the activities requiring closest control and surveillance were immediately obvious. Second, it dictates a total time duration of 350 hours thereby offering management the extremely important quantitative characteristic for the entire project.

FLOAT CONSIDERATIONS

With the critical path defined, SGC management would only need the float data to maintain a strict control over the project schedule dictated by the foregoing PERT approach. Therefore the total, interference, free, and independent activity floats were computed and compiled in Table 12. No attempt was made here to illustrate the myriad of schedules that could result, such examples were presented in Chapter III. However, this information should be available to management as a useful day-to-day control monitor and is therefore presented herein.

Activity	Total	Floats Interference	Free	Independent
1-2	0.0	0.0	0.0	0.0
2-3	184.2	184.2	0.0	0.0
2-4	182.3	182.3	0.0	0.0
2-5	184.5	184.5	0.0	0.0
2-6	0.0	0.0	0.0	0.0
2-7	29.5	0.0	29.5	29.5
2-8	31.4	31.4	0.0	0.0
2-30	271.2	0.0	271.2	271.2
3-4	184.2	182.3	1.9	0.0
4-10	182.3	182.3	0.0	0.0
5-4	184.5	182.3	2.2	0.0
6-7	0.0	0.0	0.0	0.0
7-0	0.0	0.0	0.0	0.0
8-7	31.4	0.0	31.4	0.0
9-11	0.0	0.0	0.0	0.0
10-20	182.3	0.0	182.3	0.0
11-12	33.3	33.3	0.0	0.0
11-13	24.2	24.2	0.0	0.0
11-14	38.9	0.0	38.9	38.9
11-15	55.0	55.0	0.0	0.0
11-16	0.0	0.0	0.0	0.0
12-14	33.3	0.0	33.3	0.0

TABLE 12

FLOATS : WAS PROJECT

Activity	Total	Floats Interference	Free	Independent
13-14	24.2	0.0	24.2	0.0
14-17	11.1	11.1	0.0	0.0
14-18	0.0	0.0	0.0	0.0
15-14	55.0	0.0	55.0	0.0
16-14	0.0	0.0	0.0	0.0
17-18	11.1	0.0	11.1	0.0
18-19	0.0	0.0	0.0	0.0
19-20	3.3	0.0	3.3	3.3
19-21	0.0	0.0	0.0	0.0
20-22	0.0	0.0	0.0	0.0
20-23	15.0	0.0	15.0	15.0
20-27	85.8	0.0	85.8	85.8
21-20	0.0	0.0	0.0	0.0
22-23	0.0	0.0	0.0	0.0
23-24	0.0	0.0	0.0	0.0
24-25	0.0	0.0	0.0	0.0
25-26	0.0	0.0	0.0	0.0
26-27	0.0	0.0	0.0	0.0
27-28	0.0	0.0	0.0	0.0
28-29	0.0	0.0	0.0	0.0
29-30	0.0	0.0	0.0	0.0

TABLE 12 (cont.)

FLOATS : WAS PROJECT

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

As stated in Chapter I the goal of this thesis is to show that software programs can be managed using modern planning and scheduling methods. To attain that objective a specific software program, the WAS Project, was investigated and operated on in conformance with the dictates of the PERT philosophy.

In Chapter V the WAS Project was submitted to the rigorous approach of PERT and Figure 16, the finalized PERT network for the project, was generated. The mere existence of that chart is evidence of PERT's applicability in the software domain. However, even more conclusive and significant information can be derived. The PERT chart specifies a required time duration of 350 calendar hours to complete and fulfill the obligations of the entire program. The time put in by this writer in developing the final chart, including all data compilation, interviews with SGC engineers, computation, drawings, etc., was approximately 100 hours. The total calendar hours, then, required by the PERT scheduled project were about 450. As previously reported the SGC Company was granted $5\frac{1}{2}$ months to do the job; allowing for vacation time in the month of July the allotted calendar hours were slightly in excess of 900, or twice the time the PERT schedule required. Considering that actual performance overran the allotted 900 hours by 30% one must conclude that a good case is indeed made for the PERT approach.

Based on the investigation and analysis chronicled in this thesis this writer firmly believes that PERT can be an effective if not necessary, tool for the manager of software as well as hardware programs. There are four main reasons for this conclusion. First,

. PERT forces project managers to plan in a logical, step-by-step fashion.

By enforcing a disciplined planning and scheduling function a direction is maintained and floundering is greatly decreased. In itself this feature makes the use of PERT for software programs almost a must. No one can deny that many R and D programs have been discontinued because of the lack of results even after long months of effort. Many of such programs, Chapter I cited several examples, involved little or no planning; indeed, the discipline of the PERT method was totally absent. Second,

. PERT demands planning all down the line because each sub-network engineer must plan the activities under his span of control.

If a sub-project engineer allows his part of the overall project to lag or change direction frequently and aimlessly he will eventually affect the big picture. The whole program could suffer because of one poorly planned sub-project. This situation leads to the third important contribution of PERT planned software programs.

. PERT focuses attention on critical elements that may need correction.

Aside from its basic goal of establishing a critical path, PERT also highlights possible trouble-spots before they erupt or as they develop. This is extremely important in software programs where major troubles can arise during the course of a project that even the most imaginative engineer may not foresee. Therefore it is of the utmost importance to software program managers that:

. PERT permits a forward-looking control. Delays that may affect succeeding activities or sub-projects can be pinpointed in advance.

It seems a logical and necessary conclusion that PERT has unlimited potential in software and R & D programs. Yet many managers still refuse strict discipline over such projects. Basically their opposition boils down to two arguments: 1) It costs too much! and 2) How can time estimates be made for software programs where activities are undefined at the start?

At best the arguments are weak but so frequently encountered that this writer felt obliged to mention them. First, it does not cost too much; any stories about great expense are myths and nothing more. In a 1964 textbook, Koontz and O'Donnell state "... it (PERT) apparently involves rather less expense than might be thought. Setting up the network, its analysis, its interpretation, and reporting from it, probably requires little, if any, more expense than most other planning and control techniques."[1]

The second argument provides further ammunition for the necessity of a PERT discipline in software areas. If, as stated, the activities are undefined, how does one start the project? Does he cautiously sample one approach and then another in a quest for a "good" one, or does he proceed in all directions at once exploring here and there in hap-hazard fashion? The arguing manager will offer a hasty "No" answer but he is then forced to agree that some prior planning is necessary. Upon further deliberation he will usually admit that defining some of those "undefinable" activities is the proper way to start. And it turns out that such attempts at activity definition have surprisingly simple and accurate

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1. Koontz, H., and O'Donnell C., Principles of Management, 3rd Edition, New York, 1964, p.578.

results. The enforced regimentation of the PERT technique can clear up so many of the so-called grey areas so often described but never attacked. With PERT they are not only attacked, they are defined and controlled. The activity dictionary for the WAS Project on page 102 is conclusive proof of the utility of the method.

One final conclusion of significance remains. PERTing the WAS Project permitted management by exception. A tighter, more controlled and coordinated effort was indicated and less reliance on higher management could have been realized had the PERT schedule been utilized.

In summation, this writer has two recommendations to offer the managers of software and R & D programs. First, when a non-hardware program is initially funded, adopt a PERT-like method of planning and scheduling. The unpleasant situations quoted in Chapter I make effective planning vital. The logical, decisive approach of PERT will prove invaluable before, during, and after the project duration.

Secondly, it is recommended that the greatest emphasis be placed on the activity time estimates. The accuracy of the entire PERT approach is completely dependent on the validity of the time estimates. PERT planned programs in the past have been successful because "... engineers will be willing to make a variety of estimates and will do their level best to beat the pessimistic estimate." If time and funding permit, an analysis of variance is strongly recommended to determine the feasibility of possible alternate activities. In that way activities with the least variance in expected time duration can be selected and the resultant PERT chart will be so much more accurate and reliable. The PERT technique can therefore aid management in its decision making function as well as in its planning, scheduling, and controlling projects in the software category.

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2. Ibid., p.577.

CHAPTER VII

CRITICAL EVALUATIONS

May 12, 1965

Dear Mr. Mielo,

Congratulations on a fine thesis which addresses itself to a problem of increasing significance in the defense industry today - the control of software programs.

The thesis is well organized and the flow of discussions from one subject to another is both smooth and logical.

Chapter II is an excellent "quickie" course in PERT fundamentals.

The case history in Chapter IV of the planning, scheduling, and control of the WAS program using (or perhaps misusing) "somewhat simplified Gantt Charts" is amazing. The frightening aspect of the case is the view that .... "the WAS program was a successful effort" .... in spite of the apparent abandoning of all controls and the resulting schedule and budget overruns. If this program is typical (and I suspect that it is) there can be no doubt that more rigorous planning and controls are urgently needed on software programs. Perhaps a few additional case histories in Chapter IV would add emphasis to the problem.

Chapter V aptly illustrates that PERT can be used to install the controls which the WAS program sadly lacked. I agree fully with your conclusion in Chapter VI that the control of software programs can be achieved only "by enforcing a disciplined planning and scheduling function" ... such as PERT.

Again, I congratulate you for a job well done. I wish you the very best in your future endeavors.

James I. Anderson
Engineering Group Leader

May 13, 1965

Dear Mr. Mielo,

As an engineer whose duties include the planning and scheduling of study programs, which are considerably smaller in scope than the WAS project, I found your thesis timely and interesting.

The thesis is well organized. Starting with Chapters II and III, which are a fairly good beginner course in PERT, it flows smoothly to your case history in Chapters IV and V and then to your summary.

Your paper supports my feelings that, with effort, R & D projects can be realistically planned and scheduled. While I'm not sure that PERT is the only or even the best approach to the problem of R & D planning, it does provide a control technique in an area where, in general, control is sorely lacking.

Some areas I would liked to have seen discussed in more detail are (1) organization of company wide standardized PERT methods including such aids as activity breakdown sheets, universal balloon-type network diagrams, etc., and (2) activity variance and its effects on a large project.

In closing, I congratulate you on a fine paper and thank you for the opportunity of reading a paper which provided me with some very pregnant thoughts.

Good luck in your future endeavors.

John F. Wallace
Project Engineer

REFERENCES

Aalseth, J. E., "Hints for Reliability Engineers on Technical Proposals," Evaluation Engineering, Vol. 3, No. 5, September/October, 1964, p. 41.

Aerospace Corporation, The Operational PERT System, August, 1961, Report : TDR - 930 (2408) - TR-1.

Agresta, Anthony I., Jr., Program Evaluation and Review Technique, Thesis : Newark College of Engineering, 1962.

Allison, David, "Defense Cutbacks," Science and Technology, October, 1964, pp. 20-31.

Army Materiel Command Regulation 11-16, "Planning and Control Techniques for Profit Management," Vol. II, Hq. Army Material Command, Washington, D. C., August, 1963.

Beer, Stafford, Cybernetics and Management, John Wiley and Sons, Inc., New York, 1959, pp. 1-33.

Bidwell, Robert L., "Establishing the Need for an Effective Value Engineering Program," Journal of Value Engineering, Vol. II, No. 4, August 15, 1964, pp. 23-24.

Bobak, Edward L., "The Design, Implementation, and Operation of a PERT System on a Space Program," Reproduced by Armed Services Technical Information Agency, Arlington 12, Va., February 1962, pp. 1-25, Report : Aerospace Corp., El Segundo, Cal., Contract No. AF 04 (647) -930.

Busch, Robert A., Network Scheduling Of Process Plant Projects, Thesis : Newark College of Engineering, 1962.

Caro, Robert A., News Article : Long Island Newsday, Nov. 13, 1964, p. 12.

Churchman, C. W., Introduction to Operations Research, John Wiley and Sons, Inc., New York, 1957.

Conway, R. W. and Maxwell, W. L., "Network Scheduling by the Shortest Operation Discipline," Industrial Scheduling, Prentice-Hall Inc., Englewood Cliffs, N. J., 1963, pp. 277-279.

Eckman, Donald P., Systems Research and Design, John Wiley and Sons, Inc., New York, 1961.

First Symposium on Corporate Long-Range Planning, Institute of Management Sciences, Chicago, 6 June 1959.

Forrester, J. W., Industrial Dynamics, The M.I.T. Press, Massachusetts Institute of Technology, Cambridge, Mass., 1961.

Fujii, John, An Introduction to the Elements of Mathematics, John Wiley and Sons, Inc., New York, 1961, pp. 24-41, 89-108, 181-187.

Fulkerson, D. R., "Expected Critical Path Lengths in PERT Networks," RAND Corporation, Memo RM-3075-PR, Santa Monica, Calif., March, 1962.

George, F. H., Automation, Cybernetics, and Society, Philosophical Library, New York, 1959, pp. 1-45.

Goode, Harry H., and Machol, Robert E., System Engineering, McGraw-Hill Book Company, Inc., New York, 1957.

Guida, J. V. and Bruder, K. A., PERT, A Management Control System, Sperry Gyroscope Co., Report : No. 397, September, 1962.

Hall, A. D., A Methodology for Systems Engineering, Van Nostrand, Princeton, 1962.

Kast, Fremont E. and Rosenzweig, James E., "Science, Technology, and Management : an Overview," Science, Technology, and Management, McGraw-Hill Book Company, Inc., New York, 1963, pp. 16-30.

Kelley, J. E. Jr., "The Critical Path Method : Resources Planning and Scheduling," Industrial Scheduling, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963, pp. 347-365.

Kelley, J. E. Jr., "Critical Path Planning and Scheduling : Mathematical Basis," Operations Research, Vol. 9, pp. 296-320, May-June, 1961.

Koontz, Harold and O'Donnell, Cyril, Principles of Management, 3rd Edition, McGraw-Hill Book Company, New York, 1964, pp. 574-579.

Levy, F. K., Thompon, G. L., and Wiest, J. D., Critical Path Method - A New Tool for Management, O. N. R. Research Memorandum No. 97, Report : Carnegie Institute of Technology, Pittsburgh, May 25, 1962, No. AD282450.

Levy, et al, "Introduction to the Critical-Path Method," Industrial Scheduling, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963, pp. 331-346.

Lippke, James A., "The Shape of the Industry - Today," Electronic Evaluation and Procurement, Vol. 4, No. 8, August, 1964, p. 52.

Martino, R. L., Project Management and Control, Volume I, Finding the Critical Path, American Management Association, New York, 1964.

Miller, Robert W., "How to Plan and Control with PERT," Harvard Business Review, March-April, 1962.

Miller, R. W., Schedule, Cost, and Profit Control with PERT, McGraw-Hill Book Company, Inc., New York, 1963.

Mundorff, Geary L., and Bloom, William, Managing a Development Program, Bureau of Research and Development, FAA, General Precision, Inc., New York, 1960.

Murray, John C., Consideration of PERT Assumptions, Conductron Corporation, Ann Arbor, 1962.

Muth, John F., and Thompson, G. L., "Introduction," Industrial Scheduling, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963, p. IX.

Muth, J. F., "The Effect of Uncertainty in Job Times on Optional Schedules," Industrial Scheduling, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1963, pp. 300-304.

Office of the Secretary of Defense/National Aeronautics and Space Administration, PERT COST, U. S. Government Printing Office, Washington 25, D. C., June, 1962.

Peck, M. J. and Scherer, F. M., The Weapons Acquisition Process : An Economic Analysis, Division of Research, Graduate School of Business Administration, Harvard University, Cambridge, Mass., 1962.

PERT - A Dynamic Project Planning and Control Method, I B M Corp., Data Processing Division, New York, October, 1961.

PERT - Application at LMED, General Electric LMED, Utica, N. Y., 1960.

PERT Coorindating Group, PERT Guide for Management Use, U. S. Government Printing Office, June, 1963.

"PERT/COST Output Reports," Supplement No. 1, DOD/NASA PERT/COST Guide, 1963.

"PERT Guide for Management Use," U. S. Government Printing Office, August, 1963.

PERT Summary Report Phase I, Navy Special Projects Office (Government Printing Office Catalog No. D217.2 : P94/958), 1960.

PERT Summary Report Phase II, Navy Special Projects Office, (Government Printing Office Catalog No. D217.2 : P94/958-2), 1960.

PERT/TIME and PERT/COST, Management Systems for Planning and Control, Spec. MIL P-23189 (A)/(Navy), 1962.

Pollack, John C., Planning, Scheduling, and Expediting Engineering Projects with the Aid of Electronic Computers, Argonne National Laboratory, Argonne, Illinois, 1962.

Proceedings of the 1964 Systems Engineering Conference, Vol. I, Clapp and Poliak, Inc., 1964, pp. 8-15, 133-140.

A Programmed Introduction to PERT, Federal Electric Corporation, John Wiley and Sons, Inc., New York, August, 1964.

Raymond, Jack, News Article : "63,000 Will Lose Jobs at 80 Bases in U.S.", N. Y. Times, Nov. 20, 1964, p. 1.

Stires, David M. and Murphy, Maurice M., Modern Management Methods, PERT and CPM, Materials Management Institute, September, 1963, pp. 1-107.

Spriegel, William R. and Lansburgh, Richard H., Industrial Management, John Wiley and Sons, Inc., New York, 1955, pp. 1.8-1.10.

Wolf, Ellis A., Program Evaluation Review Technique, Basic and Advanced, Polytechnic Institute of Brooklyn, Division of Industrial Management, Brooklyn, 1963.

Worth, S. V., "For Assured Delivery, Consider PERT - Even for Small Production," Electronic Evaluation and Procurement, Vol. 4, No. 8, August, 1964, pp. 22-24.

Wiener, Norbert, Cybernetics, The MIT Press and John Wiley and Sons, Inc., New York, 1961, pp. 1-29.