MASTER

AN APPLICATION OF CRITICAL PATH SCHEDULING
TO DESIGN ENGINEERING
(SANS COMPUTER)

J. H. Boyd, Jr.

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Y-12 PLANT
Oak Ridge, Tennessee

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TO DESIGN ENGINEERING
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J. H. Boyd, Jr.

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ABSTRACT

The purpose of this thesis is to present a method for the planning and scheduling of design engineering projects by applying the fundamentals of critical path scheduling, sans computer. An actual case history is used and the detailed mechanics of installing the project on critical path is presented. The case history is taken from the Plant Engineering Division of the Y-12 Plant, which is operated by Union Carbide Corporation for the Atomic Energy Commission in Oak Ridge, Tennessee. This method is suitable for design engineering organizations that range in size up to 200 engineers and draftsmen.

The author sums the experience of two and one-half years of applying critical path scheduling to design engineering projects.

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CHAPTER I

THE PROBLEM AND DEFINITION OF TERMS USED

I. INTRODUCTION

Design engineering as a profession has somewhat neglected the application of new methods for planning and controlling its own production while at the same time promoting and utilizing the latest technology available in the performance of its own tasks. This may be due to the fact that a design engineer considers himself a professional, and as such does not want to condescend to the thought that his work can be put on a production line basis. However, management must be able to control and co-ordinate the many diverse activities that are present in modern design engineering projects. Design engineering schedules must be integrated with those of development, equipment procurement, and construction. Many times a project must be co-ordinated with those of other agencies and independent companies. Design engineering must be able to produce prompt and accurate status reports, time schedules, and completion dates to enable management to make binding and realistic commitments.

Critical path scheduling is a powerful tool that will provide design engineering with the capability of supplying management accurate and timely information.

II. STATEMENT OF THE PROBLEM

The purpose of this thesis is to present a detailed method for the planning and scheduling of design engineering projects. This will be done by applying the fundamentals of critical path scheduling without the use or aid of a computer. An actual case history will be used for an example and, in step-by-step fashion, present the detailed mechanics of scheduling the job on critical path. The program presented is not original but an adaptation of various ideas, experiences, and critical path fundamentals.

III. IMPORTANCE OF THE STUDY

It has become more and more important to be able to predict the completion and/or progress of design engineering projects. Schedules within one complex must be integrated with those of other areas which may be far removed, thus making the timing important and delays costly.

In some cases, the technology and general requirements for a project become so fluid that the decision to complete or abandon it will depend upon the projected completion data or present status of the project. In the past, it has been difficult to ascertain the relative progress and actual status of a job as pertains to design engineering.

This thesis will present a method for the assignment of realistic completion dates to design engineering projects, and a form in which the status of a project is readily discernible.

IV. DEFINITIONS OF TERMS USED

The following definitions are given to provide a common interpretation of certain terms used in this thesis.

Activity. Any definable and time consuming task or function to be required in a project. It is represented by an arrow.

Arrow Diagram. A pictorial representation of the activities in a project. It shows the individual activities in sequence, and the interdependence of the activities on one another. For this presentation, it will include the dates and show the critical path.

Critical Path Methods (CPM). A technique for planning and scheduling which uses the arrow diagram to show the longest path through the project, and points out the critical activities.

Critical Path. The sequence of activities on an arrow diagram that determines the length of the project. Any delay in any activity on this path will delay the whole project. There may be one or more critical paths.

Critical Path Co-ordinator. The person responsible for accumulating the data from the design groups, preparing the arrow diagram and the manpower chart, and maintaining vigil over each critical path job and reporting its progress weekly.

Customer. The person in any of the various plant process groups or divisions who writes a work order or work request requiring design engineering.

Design Engineering. The definitive engineering required to fulfill basic design parameters which includes the preparation of detailed drawings, specifications and bills of material, and embraces the basic engineering professions.

Engineering Mechanics. The design of process and utility piping systems for gases and liquids including associated equipment, such as pumps, compressors, dryers, cooling towers, and heat exchangers.

Event. A point in time identifying the beginning or ending of one or more activities.

General Mechanical Engineering. The design of process, personnel, and environmental air conditioning systems, industrial ventilation and air purification systems, process refrigeration, and general mechanical projects.

Program Evaluation and Review Technique (PERT). A method of planning, scheduling, and control developed by the Navy for its Polaris Program. It is similar to CPM except three time estimates are used rather than one. The times used for estimating are: (1) optimistic, (2) most likely, and (3) pessimistic. PERT is more suited to basic research and development programs.

V. SCOPE OF THE STUDY

This study encompasses the five departments of design engineering. The five departments are identified as follows: (1) Engineering Mechanics, (2) General

Mechanical Engineering, (3) Civil and Architectural Engineering, (4) Instrument Engineering, and (5) Electrical Engineering. The five design departments have the responsibility to take basic design criteria and goals, and to convert them into detailed drawings and specifications. This study is presented as an aid to two groups: (1) engineers and section heads who have not had experience with critical path scheduling, and (2) supervision who must plan and schedule the plant projects both internally and externally.

VI. ORGANIZATION OF THE STUDY

The presentation of this study is intended to provide a detailed method of applying critical path scheduling for design engineering without the aid or use of a computer. It will be assumed that the reader is unfamiliar with the concept of critical path scheduling, and a short example will be given to demonstrate the method.

Next, a brief description of the actual organization will be given, with attention to its industrial environment and the development of the need for a formalized method of planning and scheduling.

The case history is presented and the detailed method of establishing the job on critical path is described. Finally, the results of the present method are given, and recommendations for future applications are made.

CHAPTER II

REVIEW OF THE LITERATURE

Ordinarily, a search of the literature on a subject will produce such an abundance of material that the reviewer is overwhelmed by the quantity of subject matter. However, articles of interest and good content are difficult to find on critical path scheduling. There have been a number of articles written and published in the trade journals and industry orientated magazines, but many are repetitious and void of detailed instructions for applying critical path fundamentals.

The history of critical path scheduling will not be presented in this thesis. There is an excellent review of the development and history of CPM in the thesis presented to The University of Tennessee by Raymond Joseph Suarez in December 1963.¹

Three books were reviewed and only a brief summary of each will be presented. The literature search was made with particular attention to the application of critical path scheduling to design engineering. The subject matter of the three books did not reveal the existence of such an application; however, the material presented provides excellent background and explains the fundamentals of CPM and PERT.

¹ Raymond Joseph Suarez, "A Study of the Planning and Scheduling by the Critical-Path Method of the Bull Run Steam Plant" (unpublished Master's thesis, The University of Tennessee, Knoxville, Tennessee, December, 1963), pp 10-22.

The book, "PERT: A New Management Planning and Control Technique," published by the American Management Association in 1962,² is a compilation of articles written by various authors. This book contains good background material, but is not intended to be a format for the detailed application of critical path scheduling.

The authors of "Operations Planning and Control" devote a portion of their book to orienting management in the fundamental concepts of PERT.³ This orientation is supplemented by series of interviews in which timely questions are answered by experts who are applying PERT in various research and development projects for the U. S. Navy Department.

A new book published in 1964, "Network Analysis for Planning and Scheduling," provides the first text book approach.⁴ The book begins with simple arrow diagrams and progresses to a full scale example. The author was aware of its limitations as shown by this quotation.

²Gabriel N. Stilian and others, PERT: A New Management Planning and Control Technique. (New York: American Management Association, 1962). 192 pp.

³Arch R. Dooley and others, Operations Planning and Control (New York: John Wiley and Sons, Inc., 1964), pp. 153-204.

⁴Albert Battersby, Network Analysis for Planning and Scheduling (New York: Saint Martin's Press, Inc., 1964). 218 pp.

If asked, 'Will this book teach me all about planning and controlling a project?', the author would unhesitantly reply: 'No, nothing can do that but practical experience. Its aim is much more modest—to put you in a good position to start learning by actual practice.'⁵

A series of six articles by Borge M. Christensen were published by Machine Design in 1962. This series of articles presents basic features of project network models, with emphasis on the critical path method. In addition, it describes an engineering-development project to show how the fundamentals are applied. The entire series is referenced in the Bibliography and only the first article will be referred to here.⁶

I. LITERATURE ON APPLICATIONS OF CRITICAL PATH SCHEDULING

Critical path scheduling is only eight years old but this technique to plan, schedule, and control projects has widespread acceptance by business, industry, and the military. This technique is applicable not only to manufacturing processes but to engineering, construction, plant maintenance, research and development, and a variety of military projects.⁷

⁵Ibid., p. 12.

⁶Borge M. Christensen, "Network Models for Project Scheduling - Part 1 - Planning Phase," Machine Design, Vol. 34, No. 11, (May 10, 1962), pp. 114-118.

⁷James E. Kelley, Jr., Louis D. Wilson, and Herbert Berman, "Using Critical Path Programming," Automation, Vol. 9, No. 11, (November 1962), pp. 90-95.

The majority of the articles appearing in the technical publications and magazines are on applications of CPM to construction. The engineering construction industry has realized the most benefits from CPM not only in application to military projects but, also, to private industry.

United Engineers and Construction, Inc. has been using CPM for the past two years to plan and schedule more than thirty projects involving millions of dollars. Included are such varied facilities as chemical plants, brass mills, brewery modernization, gas generating plants, steel rolling mill facilities, and steam generating stations.⁸

Critical path scheduling enabled Hunken-Conkey Construction Company, Cleveland, Ohio, to cut construction time considerably for the huge, concrete-framed, Riverside Terrace Housing project in Cleveland. The contractor concentrated on the critical events in the arrow diagrams which he described as "exceptions." Hunken-Conkey calls this "Management by Exception."⁹

The critical path method is currently setting the pace for one of the nation's largest construction programs. This program is California's 1.75 billion dollar State Water Project which is to convey surplus water from northern California to water-short areas in the southern part of the state. CPM diagrams are

⁸E. L. Lunkenheimer, "Use Critical Path Method to Plan Complex Projects," Power Engineering, Vol. 66, No. 9, (September 1962), pp. 37-40.

⁹"CPM Cuts Construction Time on Floor Slabs," Engineering News-Record, Vol. 170, No. 2, (January 10, 1963), pp. 38-40.

used to schedule and monitor every step of the work which includes surveys and geological work, right of way acquisition, engineering design, specifications, advertising for bids, and letting the contracts.¹⁰

Contractors are making use of the critical path method, and in many state and federal government contracts the presentation of an arrow diagram is required with the bid.¹¹

One contractor won a private contract, even though he was high bidder, because his arrow diagram clearly indicated that he had the most thorough understanding of the project. The owner felt that this would result in fewer extras and a lower total cost.¹²

II. LITERATURE ON APPLICATIONS OF CRITICAL PATH SCHEDULING TO DESIGN ENGINEERING

A detailed plan or method for applying critical path scheduling to design engineering was not found in the review of the literature. Several articles in listing the possible areas of applying CPM would include design engineering in the list, but no specific references were given.

¹⁰"CPM Paces Complex Water Project for California, " Engineering News-Record, Vol. 171, No. 8, (August 22, 1963), pp. 30-32.

¹¹"CPM Moves into the Specifications, " Engineering News-Record, Vol. 169, No. 23 (December 6, 1963), pp. 19-21.

¹²Herbert Berman, "The Critical Path Method for Project Planning and Control, " The Constructor. (September 1961), p. 24.

There was one article found describing an engineering consultant firm which used CPM. The engineering and architectural consultants of Henningson, Durham and Richardson have found critical path scheduling to be a valuable tool for planning and scheduling the engineering work required in designing a large sewage treatment plant. The detailed engineering and working drawings were scheduled using critical path method. They broke the work down into logical pieces and assigned each piece a project number. This method was set up to be used with their IBM 1620 computer.¹³

The use of a computer is usually implied in most of the applications; however, it is worthy to note that no mystical manipulations are done within the computer. It does provide high speed calculations which are necessary in large projects. Arrow diagrams containing 200 to 300 activities can be manually determined.¹⁴

It is the goal of this thesis to present a method for applying critical path scheduling to design engineering that fills the void between generalized statements of applying CPM and the formal computer orientated programs. The method described in this thesis can be applied to design engineering organizations that vary

¹³R. J. Peterson, "CPM Helps on A-E Consultant Schedule Engineering Manpower," Engineering News-Record, Vol. 170, No. 26, (June 27, 1963), pp. 22-25.

¹⁴James J. O'Brien, "CPM in Electrical Construction," Electrical Construction and Maintenance, Vol. 63, No. 1, (January 1964), pp. 70-73.

in size up to approximately 200 engineers and draftsmen. Manual compilation can be used for all calculations, and the services of a computer are not required.

CHAPTER III

THE FUNDAMENTALS OF CRITICAL PATH SCHEDULING

I. INTRODUCTION

Critical path scheduling is a way of thinking—more specifically, a way of applying new techniques to the control of a situation that is essentially serial, but in which many things occur concurrently.¹

The first step is to list every activity or job that has to be done, and then put them in their proper sequence. Then an arrow diagram is constructed by representing each activity in the project by an arrow, the tail of which represents the beginning of the activity, and the head the completion. The finished diagram will contain numerous arrows, but the placement of each arrow is made easy by the simplicity and logic of the method.

When the diagram has been completed, the activity duration times, in days and manhours, are added to each arrow. The accumulated time is now determined for each event, and the path requiring the longest time is determined. This longest path is the critical path, because a delay in any one of these events will prolong and delay the whole project.

¹John W. Mauchly, "Critical Path Scheduling," Chemical Engineering, Vol. 69, No. 4, (April 16, 1962), pp. 139-154.

Generally the arrow diagram will proceed from left to right, however, an individual arrow may go up, down, right, or left. The length of the arrow is meaningless and implies no time base or importance of activity. Each arrow head terminates in a circle which is given an identifying number.

The arrow represents an activity which is defined as any time consuming task, operation, or function. Some examples and rules of the arrow diagram are shown in Figures 1 and 2.

An activity is a restraint on another event when data or information determined by that activity is necessary for the start and/or completion of another event. This relationship is shown by a dummy arrow with the head of the arrow on the event that must have the information or data, and the tail of the arrow on the event furnishing the information or data. In this presentation, the activity and event number will be the same, because each activity is terminated in an identifying circle. The continuity of the arrow diagram is maintained by the use of dummy arrows.

The numbers in the circles are for identification. The general requirements are that there be no duplication of numbers, and that the head of the arrow must be on a higher number than the tail. It is better to number the events by twos, threes, or fives rather than consecutively. If a new event is added after the diagram has been completed, it can be assigned one of the omitted numbers and the diagram will not have to be renumbered.

a. Activity B cannot start until A is completed.

b. Neither activity B or C can start until A is completed.

c. Activity C cannot start until A and B are completed.

FIGURE 1
ACTIVITY RELATIONSHIPS

a. Activities C and D cannot begin until A and B are completed.

b. Activity C cannot start until A and B are complete. (Activity B is a restraint on C.) Activity D cannot start until B is complete.

c. Dummy arrow - The dashed arrow is called a dummy and is not a time consuming activity, but only a means to keep the logical sequence intact. The dummy arrow or arrows are terminated in a circle, and numbered only to keep the sequence in order.

FIGURE 2

ACTIVITY RELATIONSHIPS (WITH DUMMY ARROWS)

To begin the arrow diagram, all activities are listed and then the arrows are connected to show the logical flow of work. As each activity is added to the diagram it is examined in relation to the other activities and then the following questions are asked:

1. What activity (ies) must be completed before this activity can start?
2. What other activity (ies) can be performed while this activity is being done?
3. What activity cannot start until this activity is finished?

II. SAMPLE CASE

A sample case will be used to set up a typical arrow diagram for a design engineering group.

For this example, three design groups will be affected. These groups will be Electrical Engineering, Mechanical Engineering, and Civil and Architectural Engineering.

The design will be for a small room to house standards or precision instruments. The floor area will be 400 square feet with a 10-foot ceiling. The temperature of the room shall be controlled at $68 \pm 0.1^{\circ}$ F with the relative humidity not to exceed 40%. The lighting level shall be maintained at 200 foot-candles.

Listing of Activities

The activities might be listed by the design departments as follows:

Electrical Engineering

1. Design calculations for lighting.
2. One-line diagram.
3. Reflected ceiling lighting plan.
4. Schematic diagram—air conditioning controls.
5. Wiring diagram.
6. Conduit plan.
7. Check drawings.

Mechanical Engineering

1. Design calculations for air flows and air conditioning.
2. Size compressor, heaters, and air handling equipment.
3. Size duct.
4. Duct layout.
5. Duct sections and details.
6. Equipment layout.
7. Check drawings.

Civil and Architectural Engineering

1. Plot plan.
2. Floor plan.
3. Structural steel layout.
4. Wall sections.

5. Ceiling plan.

6. Check drawings.

Construction of Arrow Diagram

These activities would be incorporated into an arrow diagram in the following manner. Each design group would look at its list of activities and put down the first activity that must occur, and then follow with the next logical activity. Activities that could be performed concurrently would be drawn in parallel. The arrow diagram might take the form of Figure 3. The events are shown numbered in Figure 3; the method of assigning numbers to the events will be described in Chapter V. In Figure 3, each design department has placed the activities in their logical order as determined by the three questions that are asked for each activity, namely:

1. What must be completed before this activity can start?
2. What other activities can be performed while this job is being done?
3. What activity cannot start until this activity is finished?

Note that the design departments have put their activities down in the order they would be worked provided all the information were available. No provision yet exists to show the interdependence of one design group upon the other. This relationship is shown in Figure 4.

Restraints

The word event will be used in describing the arrow diagrams, and is synonymous with activity.

FIGURE 3
ARROW DIAGRAM (EVENTS)

FIGURE 4
ARROW DIAGRAM (RESTRAINTS)

The arrow (1) from Event 5 to Event 31 signifies that the one-line diagram cannot be started until Mechanical Engineering has sized their equipment. The arrow (2) from Event 11 to Event 13 indicates that Mechanical Engineering cannot make a duct layout until Structural Engineering has completed the structural steel layout. The arrow (3) from Event 27 to Event 33 shows that Electrical Engineering cannot start the ceiling plan until Civil and Architectural Engineering has completed and designed the ceiling.

Thus far the planning of the job is evident and the restraints have been added. These restraints are very evident, and each design group is aware of their responsibility to one another. The next procedure is for each design group to add the days and hours required to complete each event. This is shown in Figure 5.

Addition of Time in Hours and Days

At Event 3, a square is shown with the number 30 in it, and under the line is the duration in days. The "30" is the best engineering estimate for the hours needed to complete this event. The "4 days" indicates the number of days in which it is determined that the 30 hours will occur. This is a professional estimate, and is made by personnel in close contact with the work to be performed. The time in hours and the duration in days is added for each event.

Accumulated Time

Figure 6 shows the addition of the accumulated time in days. The accumulated time at each event is shown by a special box with the accumulated days to that event. The procedure is as follows:

FIGURE 5
ARROW DIAGRAM (TIME IN DAYS AND HOURS)

FIGURE 6
ARROW DIAGRAM (ACCUMULATED TIME)

Starting with Mechanical Engineering, the first event is three and the time for this event is four days—this time (4) is placed at Event 3. Now continue on to Event 5 and add one day for a total of five days at Event 5. At Event 5 a choice of four different paths is available. The accumulated total at each event must be the largest total given by the various paths to reach that event. It can be seen that a total of 6 days will occur at Event 17. (The dummy arrows used with parallel events do not represent any time and are used for continuity of the diagram such as from Event 17 to Event 19.) However, it is evident that 6 days is not the largest total that can occur at Event 19. Event 13 will take the largest value between Event 5 and Event 11, since Event 11 is a restraint upon Event 13. To continue on to Event 19, the 3 days of Event 15 are added for a total of 8 days. This addition is carried on for the remaining Events 21 and 23 for a total of 12 days. This same procedure is followed for each department and for each arrow path until every event has an accumulated total number of days. In Figure 6, Event 45 has the largest total, and this point is the end of the critical path.

Figure 7 shows the completed arrow diagram with the critical path identified. Event 47 has been added to tie all paths together, and it will take the same value of the event with the largest accumulated total.

III. DETERMINATION OF CRITICAL PATH

A portion of the critical path will be traced to show how the path is determined. As stated previously, Event 45 is the very end of the path because it

FIGURE 7
ARROW DIAGRAM (CRITICAL PATH)

has the largest total accumulated days. To find the beginning, the path must be traversed in the opposite direction, remembering that when a choice of paths exists, the longest path must be chosen.

The critical path goes from Event 45 to Event 43 through dummy arrow to Event 41, to Event 39, to Event 37, to Event 33, along restraint arrow to Event 27, and so on to Event 3. The delay of any one of these jobs will directly delay the completion date of this project.

CHAPTER IV

CONCEPT OF CRITICAL PATH SCHEDULING AS APPLIED TO DESIGN ENGINEERING

A detailed method for applying critical path scheduling to design engineering will be presented by using an actual case history, and the detailed mechanics of scheduling a job on critical path will be carried out step by step. The program presented is not original but an adaptation of various ideas and critical path fundamentals. This method can be installed with very little effort and does not require the services of a computer. Critical path scheduling has been in use by the Oak Ridge Y-12 Plant Engineering Division for approximately two and one-half years. Following is a brief description of the background of the plant and its operations where the case history originated.

I. GENERAL PLANT BACKGROUND

The Y-12 Plant is located in Oak Ridge, Tennessee, and is operated by Union Carbide Corporation-Nuclear Division for the U. S. Atomic Energy Commission.

The Y-12 Plant Engineering is very versatile and adept in many areas. This flexibility is not a luxury but a necessity due to the many varied processes and operations that are performed in the Y-12 Plant. Most industries have their own

special engineering requirements but in Y-12 the activities can cut across practically all industrial processes and techniques.

Within the Engineering Division is the Design Engineering group of departments. These departments consist of approximately 130 engineers and draftsmen and are called: Engineering Mechanics, Mechanical Engineering, Civil and Architectural Engineering, Electrical Engineering, and Instrument Engineering. The size of each department is relatively stable and will consist of from 25 to 30 employees. All departments are further divided into sections which specialize in specific fields and activities. Each section will usually have from two to four engineers and from two to six draftsmen. Figure 8 shows the standard organizational structure for the Engineering Division with the Design Engineering group in expanded form.

The "customer" can be anyone in any of the various plant process groups or divisions who writes a work order or work request which requires Design Engineering services. This work order or work request is prepared by the facility engineer for the initiating division and will include general criteria, field contacts, and tentative budgeting.

Preliminary design criteria and bills of material are prepared by Design Engineering for large work orders. This preliminary information is used to prepare realistic budget figures and to provide a comprehensive scope.

FIGURE 8

Y-12 ENGINEERING DIVISION ORGANIZATION CHART

II. ESTABLISHMENT OF PRIORITY SYSTEM

Only a few years ago there was no formal method of establishing a priority for design engineering jobs. It was a matter of experience and judgment on the part of the particular design department superintendents to determine which jobs came first. Later, the facility engineers began submitting their personal priority lists to the individual design departments to use as a guide for scheduling. At present, a variation of this system is in effect with the priorities being established by the Facility Engineering Department. The priorities are distributed by the Superintendent of Design Engineering to the heads of the design departments. These priority lists are published each week, and the design engineering schedules are prepared from these priority lists. This general description of scheduling priorities in its present form will serve as a background for the presentation of critical path scheduling.

III. SELECTION OF JOB FOR CRITICAL PATH

The decision to put a job on critical path rests mainly with the facility engineer. Such items as size of job, number of design departments involved, availability of good design criteria, customer stability, and completion date are used to determine the suitability of the job for critical path.

Critical path jobs have top priority and up to 25 per cent of the available engineering manhours are scheduled on critical path jobs at any one time.

Prior to critical path scheduling, there was no way to physically see the whole job laid out in a pattern. There were schedule sheets with due dates, but there was nothing except the intuitive feel of the engineer that would point out the interdependence of one design department upon another.

IV. INSTALLATION OF CRITICAL PATH SCHEDULING

The first critical path schedule for a test project was made by Design Engineering in the summer of 1962. There was little publicity given to the beginning and the fact was known only to those involved on the first project. The project was one of top priority and contained the basic requirements for a good test case. The job called for approximately 8000 manhours of engineering.

Even with the quiet beginning of critical path scheduling, certain general rules were laid down that would serve as basic guide lines for future applications.

The general rules were:

1. Each department was responsible for detailed events. This responsibility was vested in the section head and engineer or engineers involved. This detail of listing the events required many decisions and extensive advance planning was given to the project.
2. An estimate was to be made of the manhours and days required to complete each event. Since this estimate was made by the people involved, it was felt that this should be a realistic estimate.

3. It was the responsibility of the design group affected to list all possible restraints which would affect any event under their jurisdiction.
4. Once the arrow diagrams and the critical path had been constructed and dates added, it was mandatory for each design group to stay on schedule. If any design group fell behind the schedule, a letter from the Department Superintendent to the Design Engineering Superintendent was required stating the reasons and the necessary action that had been taken to get back on schedule.

A critical path co-ordinator was responsible for the general administration of the critical path scheduling. It was his responsibility to call the meetings, prepare the diagrams, and most important, to keep up with the progress of the schedule by frequent contact with the design departments.

The critical path was not employed to use as a club over the groups involved, but as a means of portraying and following the progress of the job. The times and durations were set by the people who were proficient and knew their work. In view of this it was felt that these times and estimates should be strictly adhered to.

CHAPTER V

CASE HISTORY OF ACTUAL APPLICATION

I. OUTLINE

After the decision has been made to put a job on critical path, the first information meeting is called. All departments of Design Engineering, the facility engineer, and the customer are invited to the meeting.

Each design engineering department will usually send a section head and an engineer to the first meeting. The purpose of this meeting is to present all available criteria to Design Engineering. All aspects of the job are discussed in detail and frequent questions are directed to the customer so that there is a clear understanding of his problems, his requirements, and his purpose.

Usually the jobs that are put on critical path are of such stature that preliminary engineering has been done, and a comprehensive scope and a good engineering estimate is available. The first information meeting is usually of sufficient depth to provide each design engineering group with all the necessary information to prepare a detailed list of events that will be required to complete their portion of the design. In unusually complicated projects, or where basic criteria are found missing in this first meeting, it will be necessary to have additional information meetings.

The design engineering departments are usually given from one to three days to prepare the events and an arrow diagram. Each design department will prepare an arrow diagram with the events listed in their proper order, along with the hours and days required to complete the event.

The arrow diagrams are given to the critical path co-ordinator who places them on the master arrow diagram.

Another general meeting is called and, at this time, the restraints are determined by each design department. Next, the cumulative days are added, the final date calculated, and the critical path identified.

II. CASE HISTORY

An actual job will be used as a specific example to show how critical path scheduling is applied to design engineering. The job was small and uncomplicated—a typical "run of the mill" design job. Neither the title nor the details of the job itself are important for this presentation. The total job required an estimated 936 engineering design hours and the participation of all the design departments.

The first information meeting was called by the critical path co-ordinator for Monday at 1 P.M. The design requirements were straightforward and detailed, and firm design criteria were available. Each design department was asked to prepare their arrow diagrams and turn them in by 4 P.M. Wednesday afternoon.

III. PREPARATION OF DEPARTMENT ARROW DIAGRAM

The section head and engineer in each design department listed all the events that they felt would provide the engineering requirements for this project. After this was done, a time in hours and a duration in days were added to each event. Next, the arrow diagram for the design department was prepared by the section head and engineer. In constructing the arrow diagram the first event that had to be done was made the beginning and the following events were drawn in order. Those events which could be done concurrently were drawn in parallel. The arrow diagrams as prepared by the various departments are as shown in Figures 9 through 13.

IV. CONSTRUCTION OF ARROW DIAGRAM

The department arrow diagrams were given to the critical path co-ordinator who made the initial master arrow diagram for the complete job, as shown in Figure 14. Usually this layout was not made without consultation with the design departments.

After discussion with the design departments it was determined that Mechanical Engineering and Electrical Engineering could start at day zero (0), the first scheduled day of work on the project, but that Engineering Mechanics, Civil and Architectural Engineering, and Instrument Engineering could not start until information was available from the other design departments. In view of this, the

FIGURE 9

ARROW DIAGRAM FOR ENGINEERING MECHANICS

FIGURE 11

ARROW DIAGRAM FOR CIVIL AND ARCHITECTURAL ENGINEERING

FIGURE 12

ARROW DIAGRAM FOR ELECTRICAL ENGINEERING

FIGURE 13
ARROW DIAGRAM FOR INSTRUMENT ENGINEERING

FIGURE 14

ARROW DIAGRAM (MASTER DIAGRAM FOR COMPLETE JOB)

first events for Engineering Mechanics, Civil and Architectural Engineering, and Instrument Engineering were set to the right of the day zero line, while Mechanical Engineering and Electrical Engineering would begin at day zero.

V. ADDITION OF RESTRAINTS

After the events have been arranged and put on the arrow diagram, as shown in Figure 14, the second meeting was called to apply the restraints and complete the arrow diagram. The first order of business was to apply the restraints. The section leader from Engineering Mechanics was asked what information would be required before his design could begin. The equipment layout drawing event from Mechanical Engineering was required before the hood-purge study event could proceed, so the restraint arrow was drawn from the equipment layout drawing event to the hood-purge study event. The arrow head was put on the hood-purge study event showing that this was the event that was restrained or needed the information, see Figure 15, Arrow 1. The next restraint for Engineering Mechanics was the bid-review event. The piping drawing revision event could not begin until the bid-review event was complete, see Arrow 2, Figure 15. This completed the restraints for Engineering Mechanics.

Mechanical Engineering was asked for restraints and it was determined that there were none.

Civil and Architectural Engineering could not begin the plan-details event and the platform and details event until the bid review event of Mechanical

Engineering was completed, so Arrow 3 was added, as shown on Figure 15. Note that the revisions event of Civil and Architectural Engineering could not commence until the hopper-design event and the hopper-drawing event of Mechanical Engineering were completed (see Arrow 4, Figure 15).

There were two restraints on the power and control-plan revision event of Electrical Engineering. One restraint was the bid-review event of Mechanical Engineering (see Arrow 1, Figure 16) and the other was the control-panel drawing event of Instrument Engineering (see Arrow 2, Figure 16).

The final restraint was the instrument-application drawing event which depended on the completion of the service piping flow-diagram event of Engineering Mechanics (see Arrow 3, Figure 16).¹

VI. NUMBERING EVENTS

After the restraints have been added, the events can be numbered. It is important to have the head of each arrow on a higher number than the tail. This procedure will assure the correct continuity of the diagram. The numbering should not be made consecutively but by twos, threes, or fives so that extra events can be

¹One type of restraint which is not clearly shown in this example is the need for vendor information. Vendor information is frequently needed before certain phases of definitive engineering can begin. It is advisable to include this type of restraint on the arrow diagram, and inform the Purchasing Department that the vendor information will be needed on a certain date.

FIGURE 16

ARROW DIAGRAM (PARTIAL NUMBERING EVENTS)

added without renumbering the diagram. It is likely that revisions will occur and the new events may be assigned numbers from those that were omitted.

The beginning of event numbering is shown in Figure 16. Mechanical Engineering is arbitrarily chosen as the beginning and the numbering proceeds as follows: Equipment layout event (Event 2) starts the sequence and, following the arrow toward the restraint, Event 4 is assigned to the equipment layout event, Event 6 to the dummy activity, and Event 8 to the hood-purge study. Since there is a restraint on the piping-drawing event from Mechanical Engineering and, remembering that the arrow head of the event must be larger than the tail, the numbering goes back to the advance B/M event to which Event 12 is assigned, Event 14 is assigned to the bid time, Event 16 to the bid review, and Event 18 to the service piping flow diagrams. The events are numbered in this manner for the complete arrow diagram, as shown in Figure 17.

The very end event of each design department is common and in the final diagram will terminate in the same event, but at this stage the events may be numbered or left blank. The final step in completing the arrow diagram is to tie the end points together, as shown in Figure 18.

VII. ACCUMULATED TIME IN DAYS

The next procedure is to add the accumulated days to each event, see Figure 19. By inspection it can be seen that the project starts with Mechanical Engineering and the accumulation will start here. However, the start can be made

FIGURE 17

ARROW DIAGRAM (COMPLETE NUMBERING EVENTS)

FIGURE 18

ARROW DIAGRAM (FINAL EVENT)

FIGURE 19

ARROW DIAGRAM (PARTIAL ACCUMULATED DATES)

with any department and, by following the arrows, the same results will be obtained. The accumulated days for each event will add as follows: Beginning with Event 2, the total is 10 days; the total is 20 days at Event 4, 20 days at Event 6, 25 days at Event 8, and, since there is a restraint on Event 18, the sequence proceeds back to Event 12. The total is 20 days at Event 12, 35 days at Event 14, 40 days at Event 16, and at this point, Event 18 will take the largest of the accumulated days of Event 16 and Event 8 plus five days. The largest total is 40 days for Event 16 and this total is given to Event 18. Event 18 (the service piping flow diagram) is a restraint on Event 46. The service piping flow-diagram event could be finished with an accumulated total of 30 days, but the total at Event 18 will be 40 days because of Event 16. A dummy event can be inserted between Events 8 and 18. This event (Event 10) will save 10 days on the restraint to Event 46 (see Figure 20). The restraint is removed from Event 18 and relocated to the new Event 10. Note that the continuity of the arrows is maintained and that the head always rests on a higher number. To continue, the total is 40 days for Event 18, 45 days at Event 20, 50 days at Event 22, 60 days at Event 24, and 65 days at Event 25. Engineering Mechanics will complete the design requirements in 65 working days from the day zero. In order to complete the accumulated total days for Mechanical Engineering, go back to Event 26 where the total is 45 days. The sum is 55 days for Event 28, 60 days for Event 32, and 65 days for Event 33.

Event 34 of Civil and Architectural Engineering starts with a 40-day accumulated total from Event 16. This means that this department will not begin work on this project for 40 working days. The final total for Civil and Architectural Engineering is 62 days at Event 42. This same procedure is followed for all events and the completed accumulated total is as shown in Figure 20.

VIII. DETERMINATION OF CRITICAL PATH

The next step is to determine the critical path. The department having the largest total accumulated days on its final event will be the beginning of the critical path. The accumulated totals for the last event of each department are as follows: 65 days for Engineering Mechanics, 65 days for Mechanical Engineering, 62 days for Civil and Architectural Engineering, 62 days for Electrical Engineering, and 65 days for Instrument Engineering. Since there are three departments having the same number for the largest accumulated total days, the critical path will assume three separate routes. The occurrence of three critical path routes on an arrow chart for design engineering is infrequent but does not present any undue problems. The point to remember is that any event is critical which, if delayed in completion, will add the same delay to the end date of the project.

To determine the critical path, begin with the largest value of accumulated days. In this case there are three starting points and it makes no difference which one is chosen first. The route to Event 25 will be used as the first starting point, as given in Figure 21. The critical path will proceed from Event 68 to Event

FIGURE 20

ARROW DIAGRAM (COMPLETE ACCUMULATED DATES)

FIGURE 21

ARROW DIAGRAM (CRITICAL PATH 1)

25, from Event 25 to Event 24, and from Event 24 to Event 22. At Event 22 there are two routes to follow but only one is on the critical path. The path from Event 22 to Event 20 to Event 18 is five days, and the path from Event 22 to Event 18 is ten days. The path from Event 22 to Event 18 is the longest and so it is the critical path.

A point to remember in determining the critical path is that the route is always from the head of the arrow to the tail. Figure 21 continues the critical path. The path will proceed from Event 18 to Event 10, from Event 10 to Event 8, from Event 8 to Event 6, from Event 6 to Event 4, from Event 4 to Event 2, and from Event 2 to day zero. This sequence constitutes one route of the critical path.

The second critical path will be traced from Event 68 to Event 33 (see Figure 22). The path proceeds as follows: From Event 68 to Event 33, from Event 33 to Event 32, from Event 32 to Event 28, from Event 28 to Event 26, from Event 26 to Event 16, from Event 16 to Event 14, from Event 14 to Event 12, from Event 12 to Event 2, and from Event 2 to day zero.

The third and last path starts from Event 68 and continues to Event 67 (see Figure 22). The path goes from Event 67 to Event 66, from Event 66 to Event 64, from Event 64 to Event 54, from Event 54 to Event 52, from Event 52 to Event 50, from Event 50 to Event 48, from Event 48 to Event 46, and from Event 46 to Event 10. From Event 10 to day zero on the critical path is the same as described in the first path.

The completed critical path for all three paths is shown in Figure 23.

FIGURE 22
ARROW DIAGRAM (CRITICAL PATH 2)

FIGURE 23

ARROW DIAGRAM (COMPLETE CRITICAL PATH)

IX. DETERMINATION OF EVENT DATES AND COMPLETION DATE

The critical path is now complete except for the calculation of the actual date for each event and the completion date. The event duration in days is always in working days. The beginning date for the specific example was set for a Monday. A partial calendar is shown in Figure 24. The start date is noted on July 22, and the accumulated working days are totaled in the upper right hand corner of the date square. For example, on July 26, four working days have passed so a "4" is in the upper right hand corner of the July 26 square. Saturdays, Sundays, and holidays are omitted when adding the accumulated days. If a Saturday or Sunday were scheduled for work, then these days would also be counted. Now it is an easy matter to add the event dates to the arrow diagram. All that must be done is to look on the arrow diagram and see what the accumulated total days for the event are, then refer back to Figure 24 and determine the actual date. An example (see Figure 25) will show this procedure. The total accumulated days at Event 2 is 10 days. Figure 24 shows a "10" in the upper right hand corner of August 5. Thus, August 5 will be the due date for Event 2. The same procedure is followed for Event 4 and the date is August 19. Dates for all the events are added in this manner which makes the completion date fall on October 22. The arrow diagram is complete.

The arrow diagram is printed and copies are distributed to the design departments.

JULY

S	M	T	W	T	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	Start 22	23	24	25	26	27
28	29	30	31			

SEPTEMBER

S	M	T	W	T	F	S
1	Holiday 2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30					

AUGUST

S	M	T	W	T	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

OCTOBER

S	M	T	W	T	F	S
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31		

FIGURE 24

PARTIAL CALENDAR

FIGURE 25

ARROW DIAGRAM (COMPLETE)

CHAPTER VI

CONSTRUCTION OF ENGINEERING AND DRAFTING CHARTS, SUMMARY SHEET, AND MANPOWER CHART

I. ENGINEERING AND DRAFTING CHARTS

Each design department prepares an engineering and drafting chart. The purpose of the engineering and drafting chart is to provide an estimate of the anticipated engineering and drafting manhour requirements. This chart is prepared by the section head and engineer assigned to the project. The abscissa of the chart is in weeks. The weeks are divided into five parts to represent the working days of the week. The ordinate is in manhours and each division represents one man-hour. The engineering and drafting chart is prepared from the completed arrow diagram. A detailed description of the chart for Engineering Mechanics will be given.

It is determined from the completed arrow diagram (Figure 25) and the calendar (Figure 24) that fourteen weeks will be required to complete the project. Starting with zero, fourteen weeks are marked off on the abscissa of the engineering and drafting chart, as shown in Figure 26. The ordinate is in manhours and each square represents one manhour. Since the weeks are actually divided into days, the height of the ordinate will represent manhours per day. The chart begins with zero even though Engineering Mechanics does not begin until after the project has been

FIGURE 26

ENGINEERING AND DRAFTING CHART FOR THE

ENGINEERING MECHANICS DEPARTMENT

under way for four weeks. The date is given for the beginning of each week. For example, July 22 is represented by the first square to the right of zero. The second square represents Tuesday the 23rd, the third square Wednesday the 24th, the fourth square Thursday the 25th, and the fifth square represents Friday, July 26. Saturday and Sunday, nonscheduled working days, are omitted and the next week begins with July 29.

Referring to Figure 25, the first event for Engineering Mechanics is Event 8 which begins August 19 and requires five days and 24 manhours to complete. The section head and engineer decide that this event will require engineering only, and the 24 hours are put on the chart with four hours scheduled for Monday and five hours for each day remaining in the week. It is customary to put the drafting hours on the bottom and the engineering hours on top. However, when no drafting hours are scheduled, the engineering hours will start from zero.

The next event for Engineering Mechanics is Event 10 which starts August 26 and requires five days and 32 manhours to complete. The section head and engineer estimate that 28 manhours will be given to drafting and four hours will be for engineering. Six hours of drafting per day are scheduled for August 26, 27, and 28 and five hours per day for August 29 and 30. Two hours engineering are scheduled on August 29 and two hours on August 30. There are two weeks in which Engineering Mechanics cannot work on the project due to restraint on Event 16. However, work can begin on Events 20 and 22 on September 17. It is estimated that Event 20 will require eight hours drafting and four hours engineering in the

next five days, and that Event 22 will require four hours engineering and eight hours drafting in the next five days. The engineering and drafting hours for these two events are totaled and put on the chart. Four hours drafting are scheduled for Tuesday, September 17, and three hours per day for September 18, 19, 20, and 23. The engineering hours are scheduled two hours per day beginning on Wednesday, September 18 and running through September 23.

Event 22 continues for five more days with 48 (60 minus 12) manhours remaining. The time is divided between drafting (40 hours) and engineering (8 hours). The drafting is scheduled for eight hours per day for five days beginning September 24 and ending September 30. The engineering is scheduled two hours per day for four days beginning September 24 and ending September 27.

The final event for Engineering Mechanics is Event 25 requiring 16 hours of drafting and eight hours of engineering. The drafting starts on October 15 at the rate of three hours per day through October 18 and four hours on October 21. Three hours of engineering are scheduled for October 17 and October 18, and two hours for October 21. This completes the engineering and drafting chart for Engineering Mechanics.

The engineering and drafting charts for Mechanical Engineering, Civil and Architectural Engineering, Electrical Engineering, and Instrument Engineering are shown in Figures 27 through 30. It should be noted that Civil and Architectural Engineering took advantage of the surplus time provided by the restraint on Event 32, and extended the hours over a longer period of days than shows on the

FIGURE 27

ENGINEERING AND DRAFTING CHART (MECHANICAL DEPARTMENT)

FIGURE 28

ENGINEERING AND DRAFTING CHART (CIVIL
AND ARCHITECTURAL DEPARTMENT)

FIGURE 29

ENGINEERING AND DRAFTING CHART (ELECTRICAL DEPARTMENT)

FIGURE 30

ENGINEERING AND DRAFTING CHART (INSTRUMENT DEPARTMENT)

arrow diagram. This is advantageous at times when it is desired to spread the manpower over a greater number of jobs.

Finally, the engineering and drafting charts are approved by the department superintendent and given to the critical path co-ordinator.

II. SUMMARY SHEET

The summary sheet is prepared from the engineering and drafting charts by the critical path co-ordinator. The summary sheet for engineering and drafting time is taken directly from the engineering and drafting charts. Figure 31 shows the engineering and drafting hours accumulated per week throughout the schedule of the project. Figure 32 shows the completed summary sheet with the grand totals, which is used to make the manpower chart.

III. MANPOWER CHART

Only the totals per week are used in making the manpower chart (see Figure 33). This chart gives at a glance the engineering and drafting requirements for the job at any particular period in its progress. There is one other chart, entitled "Jobs on Critical Path," that is used in the scheduling procedure. This chart is prepared only when a new job is put on critical path or whenever the dates are beginning to push toward the right end of the chart, and will be redrawn about every six or eight weeks. Figure 34 shows the over-all job when it was first added, and Figure 35 when the over-all job is about 40 per cent finished. This chart gives

Engineering Hours	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
	Eng. Mech.					24	4			8	8			6	2	52
	Mech. Eng.	10	10	30	30				16	20	20	4		32	8	180
	C. & A. Eng.									12	15	11	10	9		57
	Elect. Eng.	24	16							12	1	5	5	21		84
	Inst. Eng.							16	32	8			16	4		76
	Total Eng. Hours	34	26	30	30	24	4	16	48	60	44	20	31	72	10	449

Drafting Hours	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
	Eng. Mech.						28			13	35	8		12	4	100
	Mech. Eng.			20	20						32	40	56	12		180
	C. & A. Eng.									12	15	15	15	6		63
	Elect. Eng.										32	20	20	4		76
	Inst. Eng.							16	8	16			16	8	4	68
	Total Draft. Hours	-	-	20	20	-	28	16	8	41	114	83	107	42	8	487

FIGURE 31

ENGINEERING AND DRAFTING SUMMARY SHEET (WEEKLY TOTALS)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Eng. Mech.					24	4			8	8			6	2	52
Mech. Eng.	10	10	30	30				16	20	20	4		32	8	180
C. & A. Eng.									12	15	11	10	9		57
Elect. Eng.	24	16							12	1	5	5	21		84
Inst. Eng.							16	32	8			16	4		76
Total Eng. Hours	34	26	30	30	24	4	16	48	60	44	20	31	72	10	449

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Eng. Mech.						28			13	35	8		12	4	100
Mech. Eng.			20	20						32	40	56	12		180
C. & A. Eng.									12	15	15	15	6		63
Elect. Eng.										32	20	20	4		76
Inst. Eng.							16	8	16			16	8	4	68
Total Draft.	-	-	20	20	-	28	16	8	41	114	83	107	42	8	487
Hours Total Hours	34	26	50	50	24	32	32	56	101	158	103	138	114	18	936

FIGURE 32

ENGINEERING AND DRAFTING SUMMARY SHEET (GRAND TOTALS)

FIGURE 33
MANPOWER CHART

FIGURE 34

JOBS ON CRITICAL PATH ON JULY 31

FIGURE 35

JOBS ON CRITICAL PATH ON SEPTEMBER 16

engineering management a ready reference for the manpower requirements for the existing jobs on critical path, and is an aid in planning for the addition of future jobs to critical path.

CHAPTER VII

RESULTS

I. FOLLOW-UP PROCEDURES

The critical path co-ordinator makes a weekly check with each design department superintendent to ascertain if his department is on schedule for each job on critical path. If a particular design department is falling behind, it is the responsibility of the Design Department Superintendent to inform and to give an explanation to the Design Engineering Superintendent.

II. STATISTICAL SUMMARY

Every job or portion of a job that has been placed on critical path has finished as scheduled.

In a recent two-year period, 34 jobs have been scheduled on critical path. There were 64,633 engineering manhours scheduled and 71,258 engineering man-hours actually spent on the 34 critical paths. The jobs ranged in size from 237 to 7,804 scheduled hours, and the duration varied from two and one-half to twenty-seven weeks.

The actual hours spent on each critical path job are summarized in Column 2 of Table I. The estimated hours as determined from the critical path are given in Column 3. Column 4 lists the algebraic difference of actual hours spent

TABLE I
CRITICAL PATH SUMMARY

Critical Path Job Number	Time Spent (hrs)	Critical Path Estimate (hrs)	Actual Time Spent Minus Critical Path Estimate (hrs)	Deviation ⁽¹⁾ (%)
1	10,832	7,804	3,028	38.9
2	2,872	2,064	808	39.1
3	2,293	1,816	477	26.3
4	447	460	- 13	- 2.8
5	1,101	1,024	77	7.5
6	1,122	998	124	12.4
7	1,171	1,407	- 236	- 16.8
8	1,268	1,050	218	20.8
9	2,242	2,278	- 36	- 1.6
10	1,585	1,680	- 95	- 5.6
11	970	973	- 3	0.0
12	225	237	- 12	- 5.1
13	794	1,136	- 342	- 30.1
14	2,577	1,999	578	28.5
15	6,844	5,872	972	16.5
16	3,021	3,059	- 38	- 1.3
17	1,938	1,866	72	3.9
18	2,419	2,345	74	3.2
19	798	667	131	19.7
20	343	401	- 58	- 14.5
21	2,745	2,489	256	10.3
22	1,354	1,061	293	27.6
23	1,634	1,585	49	3.1
24	1,133	914	219	24.0
25	1,114	936	178	19.1
26	477	662	- 185	- 28.0
27	524	438	86	19.7
28	2,357	2,154	203	9.5
29	2,079	2,320	- 241	- 10.4
30	1,392	1,550	- 158	- 10.0
31	4,916	4,661	255	5.5
32	609	587	22	3.8
33	3,881	3,933	- 52	- 1.3
34	2,181	2,207	- 26	- 1.2
Total	71,258	64,633		

(1) Column 4 divided by Column 3 times 100.

minus the estimated hours. Column 5 contains the per cent deviation for each job, and is assigned a positive number if the actual hours exceed the estimate and a negative number if the actual hours are less than the critical path estimate.

The per cent deviation is shown plotted as a function of the chronological order of the critical path jobs in Figure 36. Approximately 60 per cent of the jobs required more hours than the critical path estimate.

There are wide variations in the per cent deviation in the first 27 jobs; however, the last seven indicate better estimates with the largest deviation approximately 10 per cent.

In Figure 37, the per cent deviation curve is shown with the average-of-four curve superimposed. The average-of-four curve was used to give a more comprehensive trend. This curve was constructed by getting the algebraic table of per cent deviation for the last four jobs (Jobs 34, 33, 32, and 31) and dividing by four to get the average per cent deviation. This procedure provided the first point and corresponds to Job 34. The second point was determined by dropping the per cent deviation for Job 34, and using per cent deviation for Job 30. All points were determined by following this procedure (Figure 37).

The average-of-four curve shows a smoothing trend and gives some indication that the estimates are beginning to fall within more narrow limits. It takes several jobs before every section leader and engineer has an opportunity to have one or more of his jobs put on critical path. The experience of having jobs on critical path is not evenly divided between the different section leaders and

FIGURE 36

PER CENT DEVIATION CHART

FIGURE 37

PER CENT-OF-DEVIATION CURVE AND AN

AVERAGE-OF-FOUR-JOBS CHART

engineers. This unequal assignment will continue to exist because the specialization of some design sections are not required in many jobs.

III. DEVELOPING MUTUAL GOALS

There is a natural and friendly rivalry between engineers of various academic backgrounds, and there are overlapping responsibilities in many areas. The design sections and engineers reap many benefits through the close association required in putting a job on critical path. The first-hand presentation of the design problems by the other groups develops a sympathetic attitude and a greater appreciation for the proficiency of their fellow employees. The dependence of one design section upon another is readily discernible, and a more co-operative attitude is immediately generated.

There is a personal contact with someone in each design group, and information can readily flow back and forth without formal transmission. The responsibility of a person to himself and to the other design sections in preparing and transmitting the proper design information on time generates a motivating attitude.

The plan ahead idea is a necessity in critical path scheduling. The events must be planned and attention given to what must be done, and in what order. The only things that can be put on critical path are decisions. If a decision is not and cannot be made, a critical path will not exist. It is the advance planning and the decision making that makes the critical path method a real and effective working tool.

IV. COMMENTS ON PREDETERMINED COMPLETION DATES

In the presentation of the case history it has been assumed that the completion date determined by the normal application of manpower was satisfactory. However, there are times when the completion date is very important and this date will be one of the main goals of the project.

When this situation exists, the first-arrow diagram is constructed, as previously described. The completion date determined in this manner will probably not fall within the required time limit. Therefore, the number of days that must be eliminated is the difference between the required completion date and the determined completion date. The total working days can be reduced by authorizing overtime or using more manpower on those events where it will decrease the days required to complete the project. Each department will review each event and modify the days required to complete each event. Now the arrow chart is redone using these new times and the completion date determined anew. If this new date does not fall within the acceptable limits, the arrow diagram is investigated again for short cuts and time-saving schemes; and, if none are found, the new date will have to be accepted or the project abandoned.

CHAPTER VIII

CONCLUSIONS

Critical path scheduling should have a definite place in design engineering planning and scheduling. The exact boundaries and limiting circumstances are yet to be determined, but a framework now exists in which much can be accomplished. The availability of a plan where every important event of a project is visible in picture form is now a reality, with the added feature of a time base built into the picture. This is an important tool for both engineering supervision and general plant management.

I. GUIDE LINES FOR PROBLEM AREAS

No method is without its vulnerable areas, and it is well to be aware of what can happen and remedies that can be applied to fortify the weak points of the plan.

The pressure of being "under the gun" is not a comfortable feeling for most people, and a feeling of resentment is readily generated. Yet this situation of being under constant pressure is developed when a project is put on critical path. The dates on the events are fixed and, since time is a dynamic dimension, the events become due in an impersonal manner.

Padding Time Estimates

One of the ruses used to relieve the time pressure is to "pad" the events in both hours and days required for completion. This act of adding extra hours and days to the events is not justified and is mainly a result of insufficient detail for the events. It seems to be a normal tendency to lump several activities into an event rather than break the project down into smaller areas of interest. Of course this can be taken to extremes, but good common sense should prevail and, if established criteria are used, the plan will be successful.

The engineer and section head can assign good engineering estimates to events that are clearly defined and be confident in their judgment. It is not necessary to resort to "padding" when this approach is taken. It should be stressed that the events should be broken down into the smallest reasonable engineering requirement.

It should be emphasized that the planning and construction of the arrow diagram must be done by technical personnel close to the job. They must be thoroughly familiar with the functional requirements for the total program, and intimately familiar with the productivity of the participating employees.

There is another advantage in detailing the events and their portrayal on the arrow diagram. The work is laid out and presented in a defined and orderly manner and, with the completion of one event, the next step is evident. Thus, there is no lost time in pursuing the completion of the project; the question of what to do next is already answered.

Criteria Requirements

Good design criteria must be available before a project can be considered for scheduling on critical path. This requirement does not imply that every detail must be presented at the beginning, but it does require that definite objectives and guide lines be set that will not fluctuate from day to day. The arrow diagram can be constructed only by putting decisions on paper. The diagram is not inflexible but, if revisions are made every week, it soon loses its effectiveness and confidence wanes in the project.

Size and Type Considerations

The maximum size of a project for a manual compilation is theoretically unlimited, but the practical number is between 300 and 400 activities. The largest number of activities scheduled by Y-12 Design Engineering was 208, and these activities required 6,100 hours of engineering manpower. Projects requiring less than 300 engineering manhours with normal completion dates are not particularly suited for formal scheduling on critical path. Projects in this size range will usually be straightforward and will probably require participation from only one to two design departments. The time spent in scheduling the job in a formal manner would take a high percentage of the allocated design manhours, and the expected return would be negligible.

The most benefits from critical path scheduling are obtained from projects that require participation from all the design departments. It is important to know in advance the interdependence of the design groups upon one another. Pinpointing

these responsibilities will permit them to receive the attention necessary to prevent delays and improve the flow of information between departments. When one design department has a restraint upon another, the department needing the information will not wait patiently for the formal transmission of the data, but will have its representative getting the information first hand from the engineering doing the design. One of the advantages of this is the recognition and solution of many minor problems that can be resolved very quickly by a brief discussion between the engineers.

There are certain projects where only two or three design groups are affected, but the design requires an overlap into the capabilities of one or more of the design groups. Borderline responsibilities exist between all phases of engineering and definite boundaries are very difficult to define. By putting the job on critical path, events in these questionable areas are quickly spotted and, by assigning responsibility in the planning stage, duplication of effort is prevented.

Scheduling

Critical path scheduling has been reserved for important and high-priority design engineering projects of the plant. The critical path jobs are given the first priority ratings to make it possible to schedule sufficient design engineering manpower to complete the scheduled activities on time. The general rule has been to allocate up to twenty-five per cent of the design engineering manpower to critical path projects. It was decided that this portion of design engineering could be used effectively on critical path, and that these projects would be guaranteed to the

customer regarding schedule and completion date. Fifty to seventy per cent of design engineering manpower is scheduled on the remaining projects in descending order of priority. The completion date of these projects will vary as their position on the priority list varies. The remaining five to twenty-five per cent of design engineering manpower is reserved for field support and startup of projects already designed.

In the presentation of the case history it has been assumed that the completion date determined by the normal application of manpower was satisfactory. However, there are times when the completion date is very important, and this will be one of the main goals of the project.

When this situation exists, the first-arrow diagram is constructed as described in this thesis. The completion date determined in this manner will probably not fall within the required time limit. The number of days that must be eliminated is the difference between the required completion date and the determined completion date. The total working days can be reduced by authorizing overtime or using more manpower on those events where it will decrease the days required to complete the project. Each department will review each event and modify the days required to complete each event. Now the arrow diagram is redone using these new times and the completion date determined anew. If this new date does not fall within acceptable limits, then the arrow diagram is investigated again for short cuts and time-saving schemes; and, if none are found, the new date will have to be accepted or the project abandoned.

Projects having predetermined completion dates are the most difficult to schedule. Once the arrow diagram has been constructed and an effort is in effect to allow a minimum time for every event, times may be agreed to that are unrealistic. It behooves each design department, the customer, and facility engineer to be certain that due consideration is given to the time reduction of any event, and to make certain that good engineering judgment is being administered.

Scheduling all jobs on critical path would be difficult and would develop a very formal and fixed schedule. Some time must be left for routine assignments, short duration projects, startup support, and emergency field assistance. The degree of flexibility desired will vary with the demands and application of the user.

Even though all jobs are not scheduled, this does not mean that the jobs should not be planned. The benefits of advance planning, intradepartment restraints, and an organized program are available from the planning phase of critical path, even though no hours, days, or dates are assigned.

One of the disadvantages of a large design engineering organization is the lack of personal contact between engineers of different professional backgrounds. Critical path planning and scheduling institutes and renews the personal relationship.

II. COSTS

The necessary data for determining the exact cost for putting a project on critical path have not been recorded. However, the following figures expressed in

manhours and percentages are based on Y-12 Design Engineering experience. A minimum of five manhours per design department are required to put a job on critical path. For projects requiring up to 1500 design engineering manhours, approximately three per cent will be needed for scheduling. The percentage required will decrease with an increase in job size above 1500 manhours, and will reduce to approximately one per cent for jobs requiring 10,000 design engineering manhours.

The accountable cost of the initial phase of critical path scheduling will probably be higher than the cost of traditional methods, but this is because it is more thorough, and the planning is performed at the beginning of the job. However, the savings realized by the elimination of duplicate efforts, the removal of misunderstandings and confusion, and the time saved by having a definite program to follow will more than offset the initial hours spent in preparing the critical path schedule. It is difficult to estimate how much time and money can be wasted on a project which does not have a thorough plan and schedule.

III. REVISIONS

The critical path schedule is easily revised to reflect new design requirements or to delete activities found unnecessary. The design departments concerned give the new information to the critical path co-ordinator who revises the arrow diagram, recalculates the critical path, assigns a new completion date (if required), and reissues the critical path schedule.

IV. SUMMARY

Critical path scheduling provides excellent communication and encourages teamwork with its easy-to-follow graphic form. Each individual engineer and supervisor receives due recognition for their part in the successful completion of a project. The date on each activity provides an excellent progress incentive and fills the project with many small attainable goals. The attainment of each of these goals instills either consciously or unconsciously a sense of accomplishment in the individual, which is a motivating force of its own.

Engineering management can plan and schedule design engineering projects efficiently and effectively by the application of critical path scheduling, be assured of the successful completion of the projects, and at the same time generate a new level of confidence in engineering personnel.

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