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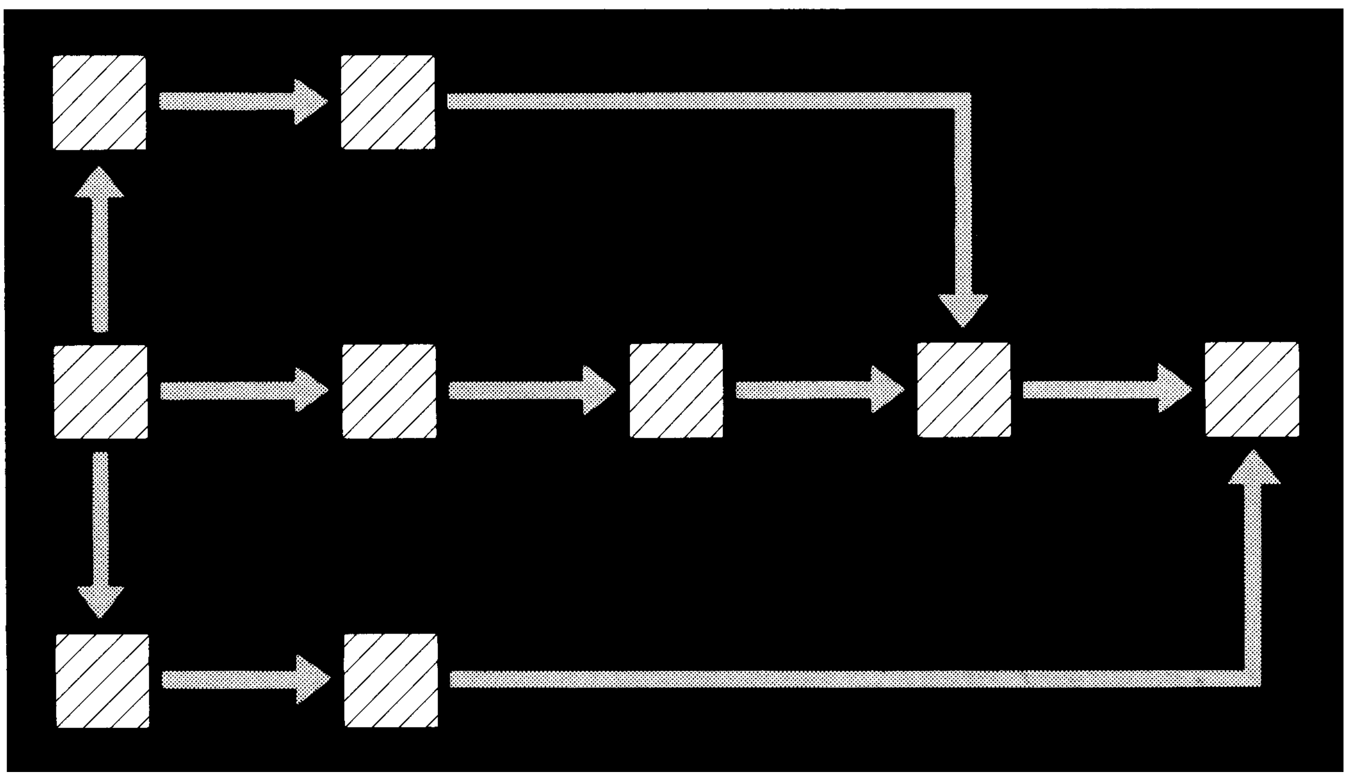
Critical Path Method Applied to Research Project Planning: Fire Economics Evaluation System (FEES)

Earl B. Anderson R. Stanton Hales



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INTRODUCTION

Network techniques are often used in scheduling projects that contain many interrelated activities. One approach that has been widely used is the critical path method, in which a network diagram depicts precedence among activities. This method also calculates their starting, float, and finishing times to identify critical activities, and it constructs a time chart to display possible project schedules.

Typically, network techniques have been used in large and complex projects consisting of thousands of activities, such as major construction and engineering projects. In the 1950's, a critical path technique called PERT (program evaluation and review technique) was developed by the U.S. Navy for managing the Fleet Ballistic Missile (Polaris) submarine project. CPM (critical path method) was developed by the DuPont Company and Remington Rand Univac for managing plant maintenance and construction work.[1] Differing--for the most part-only in the level of importance that probabilistic concepts have in their use, these mathematical optimization techniques are referred to collectively as PERT-CPM or simply CPM.

Despite the success of PERT-CPM in hardware-oriented programs, its application in resource management problems was initially limited (Davis 1968). But as CPM techniques were modified and designed to operate on the smaller new computer systems, they proved useful in smaller projects such as design and marketing of new products, maintenance and shutdown schedules, and research and development programs. Its potential was apparent for scheduling and monitoring development of the Fire Economics Evaluation System (FEES). This simulation model is being developed by the Forest Service's Pacific Southwest Forest and Range Experiment Station to relate alternative fire management activities to changes in fire management program costs and resource net values (Mills and Bratten 1982).

A survey of more than 30 available computerized CPM systems from more than 20 software suppliers showed that most routines had specific applications and were adapted to specific computer languages and hardware. None were ideally suited nor could be reasonably modified to meet the needs of developing the FEES project. Therefore, a computerized CPM package was developed under a cooperative agreement with the Mathematics Clinic of the Claremont Colleges, Claremont, California.

Since the FEES package was developed, software routines have been created elsewhere and are available for application to other small projects. Therefore, before selecting or developing a CPM system, software operable on the potential users' hardware should be thoroughly searched.

This report describes the critical path method, explains the mathematical concepts behind it, and--using the FEES project as an example--illustrates how a computerized CPM approach can be applied to a resource management or other research project.

[1]Commercial enterprises are mentioned only for information. No endorsement by the U.S. Department of Agriculture is implied.

CRITICAL PATH METHOD (CPM)

Translating a project's needs into a mathematical system requires an understanding of general stages within which the CPM routines may be applied: planning, scheduling, and controlling (more appropriately termed "monitoring" for research application).

The greatest advantage of CPM is seen at the planning stage. Here the user is required to think through a project logically and with sufficient detail to establish firm, clear project objectives, activities, and specifications. This minimizes the chance of overlooking necessary activities and goals of a project.

In the scheduling stage, CPM provides a realistic and disciplined method for determining how to attain the project objectives and for communicating and documenting the project plans clearly and concisely. A time chart is constructed to show the start and finish times for each activity, and the amount of leeway or "float" corresponding to each activity's relationship to other activities in the project.

The monitoring stage helps to focus management's attention where it is most needed: on the activities that most constrain the schedule. As activities are completed ahead of or behind schedule, CPM will generate new schedules which allow for those activities, and as technical or procedural changes are considered, CPM will indicate the effect these changes would have on the overall schedule.

In the planning and scheduling phases of CPM analysis, three basic steps are carried out:

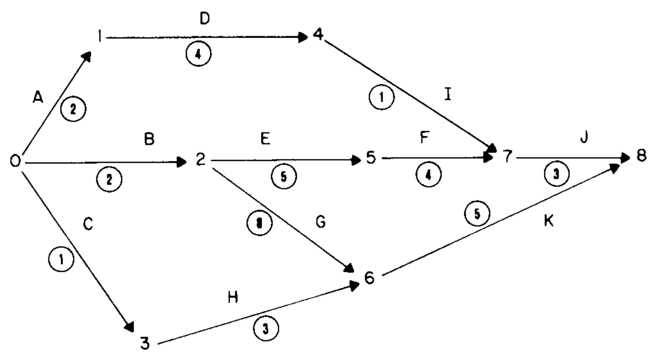

Figure 1--A network or arrow diagram for a project shows the order in which activities are to be carried out. Arrows represent activities (capital letters), arrowheads indicate the order of activities, and nodes or points (numbers) denote beginning and end of activities. Circled numbers are durations of activities in time units.

1. Constructing a network diagram to depict precedence among activities
2. Calculating start, finish, and slack or float times
3. Constructing a time chart to display results of steps 1 and *2.*

Constructing a Network Diagram

The first step in CPM analysis is constructing a network, or arrow, diagram that graphically shows the precedence relationships among project activities, i.e., the order in which activities are to be carried out. An arrow represents an activity; arrowheads indicate the order of those activities. A "node" or point denotes the beginning and end of an activity. Each node then is labeled and represents an event, defined to be the completion of all activities leading into that node. In general, integers represent nodes and capital letters represent activities.

A network diagram can be constructed given the following information: a list of all activities involved in a project and, for each activity, a list of its precedences, i.e., the other activities that must be completed (immediately) before beginning that particular activity. For example, the network diagram in *figure 1* was constructed from the following sample information (duration is expressed in time units, such as weeks or months, appropriate for a specific project):

Activity	Precedences	Duration
A	-	2
B	-	2
C	-	1
D	A	4
E	B	5
F	E	4
G	B	8
H	C	3
I	D	1
J	I, F	3
K	G, H	5

Four basic rules guide construction of a network diagram (Taha 1971):

Rule 1--*Each activity is represented by one arrow in the network.*

Rule 2--*"Dummy" activities are created whenever needed to portray the logic of the relationship between activities.* A dummy activity is depicted as a dotted arrow and represents an activity which takes no time and uses no resources. It is needed when a logical relationship between activities cannot otherwise be represented correctly. For example, suppose that in a certain project both activities C and D must precede activity F, and only activity C must precede H:

Activity	Precedences
F	C, D
H	C

To represent this situation correctly, one must make use of a dummy activity. The incorrect and correct representations of a dummy activity are shown in *fig. 2.*

Rule 3--*No two activities should be identified by the same beginning event and by the same end event.*

Rule 4--*The following questions must be answered as each activity is added to the network, to insure the network correctness:*

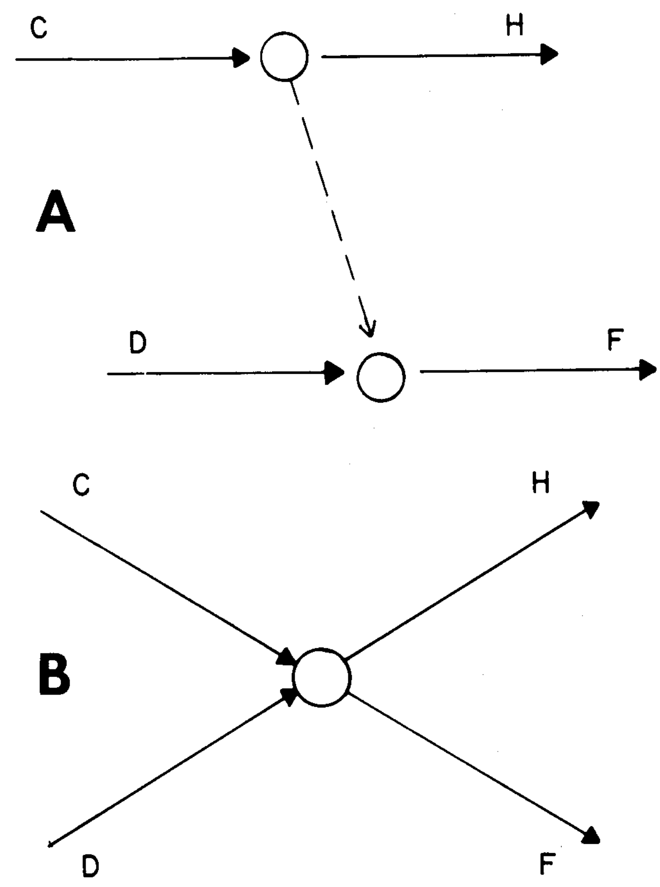

Figure 2--(A) A dummy activity (dashed arrow) correctly represents a relationship between activities that cannot otherwise be logically depicted: activities C and D must both precede F, and only activity C must precede H. (B) Incorrect representation of same relationship.

• *What activities must be completed immediately before this activity can start?*

• *What activities must follow this activity?*

Using these four rules, one can create by hand or by computer the network diagram associated with a project. However, many CPM computer routines do not explicitly create the network diagram. Instead, they store activity duration times as a (vector) list of numbers, and immediate precedences as a Boolean matrix (tables of 0's and l's) and deal with them algebraically. They are thus able to use the information that a network diagram provides without actually plotting it, and thus only make implicit use of the diagram.

Calculating Start and Finish Times

The second step in CPM analysis is calculating start and finish times for activities. Times are calculated using the precedence relationships shown in the network diagram and their durations. Start and finish times are used to determine float times associated with each activity. Float times are used to identify critical activities.

The calculations involve two phases: the "forward pass" and the "backward pass." The forward pass involves a sequence of calculations beginning at the start of the network and moving forward toward the end of the network. This phase computes the earliest possible finish time. The backward pass involves a sequence of calculations beginning at the end of the network and moving backward toward the start of the network. This phase computes the latest possible finish time.

Each activity of the network diagram (*fig. 1*) can be denoted either by its end nodes (i, j) or activity name (I). Let the earliest time event i, ETE(i), be the earliest possible starting time of the activities emanating from node i, given that the ETE of the start event is 0. For the end event, the ETE is defined as the earliest possible starting time of an activity emanating from the final node, if there were such an activity.

Let D(i, j) denote the duration of activity (i, j). Note that the dummy activities are assigned duration times of 0. Then knowing the ETE(i) for all events preceding event j, one may calculate ETE(j) with

$$ETE(j) = \max\ [ETE(i) + D(i, j)]$$

where max (the maximum) is taken overall nodes *i* for which (i, j) is a defined activity.

For example, in the project in *fig. 1*, ETE(0) = 0 because it is the start node,

$$ETE(2) = \max\ [0 + 2] = 2,\ ETE(3) = \max\ [0 + 1] = 1$$

and

$$ETE(6) = \max\ [\ 1 + 3,\ 2 + 8] = 10.$$

The ETE(i) can thus be calculated by beginning at the start of the network and moving toward the end of the network. These calculations, or an equivalent set of calculations, constitute the forward pass.

It is conventional to define the project time as the ETE of the end event. In this case, the project time is the minimum amount of time needed to finish the project. Occasionally, however, the project manager may choose to redefine the project time by lengthening it.

Now let the latest time event i, LTE(i), be the latest possible finish time of all activities coming into event i, given that the LTE of the end event is set equal to the project time. Thus, LTE(i) represents the latest time event i may occur, with the condition that the project time is still met.

Then, knowing the LTE(j) for all events succeeding i, one may calculate LTE(i) by using the following formula:

$$LTE(i) = \min\ [LTE(j) - D(i, j)]$$

where min (the minimum) is taken over all nodes j for which (i, j) is a defined activity.

For example, in the project in *fig. 1,* LTE(8) = 15 because it is the finish node,

$$LTE(6) = \min\ [15 - 5] = 10$$

and

$$LTE(7) = \min\ [\ 15 - 3] = 12.$$

The ETE and LTE values for this network are these:

Event	ETE	LTE
0	0	0
1	2	7
2	2	2
3	1	7
4	6	11
5	7	8
6	10	10
7	11	12
8	15	15

The LTE(i) can thus be calculated by beginning at the end of the network and moving toward the start of the network. These calculations, or an equivalent set of calculations, constitute the backward pass.

Using the results of forward and backward passes, one completes the basic CPM calculations by using early and late times for events to determine the allowable start, finish, and float times for individual activities.

We must define several terms. Let ES(i, j) denote the earliest possible starting time for activity (i, j) and let LS (i, j) denote the latest possible starting time. Let EF (i, j) denote the earliest possible finish time for activity (i, j) and let LF (i, j) denote the latest possible finish times. By convention, ES(i, j) = 0 for any activity (i, j) that has no precedences, and LF(i, j) = project time for any activity (i, j) that has no successors.

Now ES(i, j) = ETE(i) because the activity (i, j) may begin as soon as all of its precedences are completed, i.e., as soon as event i occurs, and LF(i, j) = LTE(j) because the activity (i, j) must finish before event j occurs. The EF(i, j) and LS(i, j) are then easy to calculate:

Table 1--*Earliest start (ES), earliest finish (EF), latest start (LS), and latest finish (LF), for the sample project* (fig. 1)

Activity	ES	EF	LS	LF
A	0	2	5	7
B	0	2	0	2
C	0	1	6	7
D	2	6	7	Il
E	2	7	3	8
F	7	11	8	12
G	2	10	2	10
H	1	4	7	10
I	6	7	11	12
J	11	14	12	15
K	10	15	10	15

$$EF(i, j) = ES(i, j) + D(i, j) = ETE(i) + D(i, j)$$

$$LS(i, j) = LF(i, j) - D(i, j) = LTE(j) - D(i, j)$$

Table 1 shows the ES, EF, LS, LF times for the project in *fig. 1*. Four floats are associated with each activity: total float, free float, safety float, and independent float (*table 2*).

Total float (TF)--Given a schedule in which each activity is initially slated to start as early as possible, the total float of activity (i, j) is the maximum amount of delay allowed in performing it, possibly delaying succeeding activities as well, but such that the project time will not be affected. That is,

$$TF(i, j) = LTE(j) - ETE(i) - D(i, j) = LS(i, j) - ES(i, j)$$

Free float (FF)--Given a schedule as that above, the free float of activity (i, j) is the maximum amount of delay allowed in the performance of the activity without affecting any succeeding activity. That is,

$$FF(i, j) = ETE(j) - ETE(i) - D(i, j) = ETE(j) - EF(i, j)$$

Safety float (SF)--Given a schedule in which each activity is initially scheduled to start as late as possible, the safety float of activity (i, j) is the maximum amount of "speeding up" allowed in the performance of the activity without affecting any preceding activity. Speeding up does not mean shortening the activity duration, but rather means beginning work on that activity before it was initially scheduled to begin. That is,

$$SF(i, j) = LTE(j) - LTE(i) - D(i, j) = LS(i, j) - LTE(i)$$

In such a schedule, the total float is also the maximum amount of speeding up allowed in the performance of the activity, possibly speeding up preceding activities as well, but such that the project does not start before time 0.

Independent float (IF)--The independent float of activity (i, j) is the amount of slack (if any) available in the scheduling of the activity, assuming that the activities preceding it occur as late as possible and that those succeeding it occur as early as possible. That is,

$$IF(i, j) = \max\,[0, ETE(j) - LTE(i) - D(i, j)]$$

Calculating float times completes the basic CPM calculations.

For every activity

$$TF \geq FF \geq IF \geq 0$$

and

$$TF \geq SF \geq IF \geq 0$$

In general, no conclusions can be drawn about the relationship between FF and SF (*table 2*).

An activity for which total float is minimal, over all activities, is said to be critical. In the normal case, where the project time is chosen as the earliest possible finish time of the project, such an activity has zero total float and no delay or speeding up is allowed in the performance of that activity. All other activities are noncritical. A critical path through the network diagram consists entirely of critical activities. There will always be at least one critical path in the network. Critical activities must be identified because they are the activities for which the greatest effort should be made to stay on schedule; any delay in one of them will delay project completion.

Table 2--*Total float (TF), free float (FF), safety float (SF), and independent float (IF), for the sample project* (fig. 1)

Activity	TF	FF	SF	IF
A	5	0	5	0
B	0	0	0	0
C	6	0	6	0
D	5	0	0	0
E	1	0	1	0
F	1	0	0	0
G	0	0	0	0
H	6	6	0	0
1	5	4	0	0
J	1	1	0	0
K	0	0	0	0

Constructing a Time Chart

The third step in CPM analysis is constructing a time chart that displays, in a useful manner, start and finish times for each activity and the floats associated with each activity. Also, the chart may show the relationship of each activity to other activities in the project.

Because many of the activities of a project have favorable total float, many time charts could represent a possible project schedule. A schedule is possible in the sense that, if available resources are unlimited, the project could be completed at the scheduled time. The two extremes are the schedule in which every activity starts as early as possible (*fig. 3a*) and the schedule in which every activity starts as late as possible (*fig. 3b*).

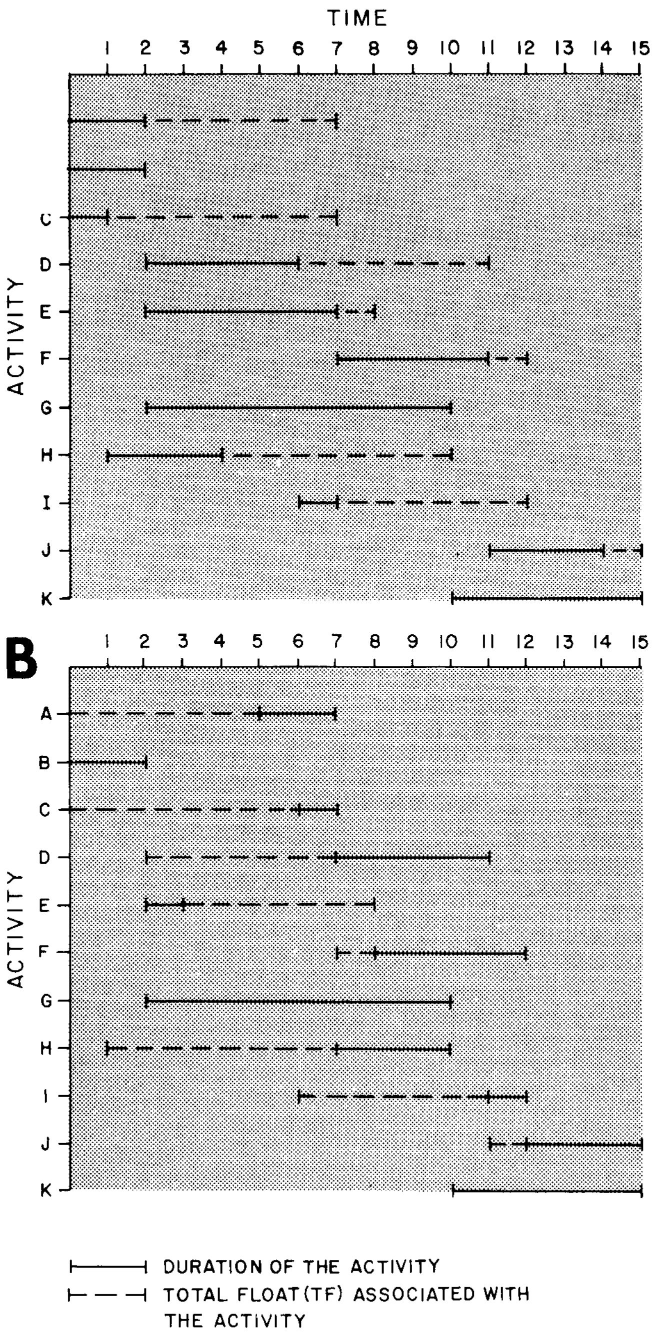

Figure 3--Time charts represent possible project schedules for the sample project *(fig. 1).* (A) Schedule in which each activity will start as early as possible. (B) Schedule in which each activity will start as late as possible.

METHODS OF SCHEDULE SELECTION

The task of choosing between different possible schedules is ultimately left to the project manager. However, methods of analysis were designed to aid in making this decision. Two of these are resource analysis and cost analysis.

Resource Analysis

Resource analysis refers to a body of techniques used to find a schedule in which the resource allocation of the project is in some sense good, such as being feasible and somewhat constant.

For example, the project in *figure 1* requires the use of two resources, A and B, and each activity of the project requires the following amounts of the resources:

Activity	Units of Resource A	Units of Resource B
A	3	0
B	6	0
C	3	0
D	0	2
E	0	2
F	2	0
G	4	4
H	5	0
I	4	0
J	0	5
K	2	0

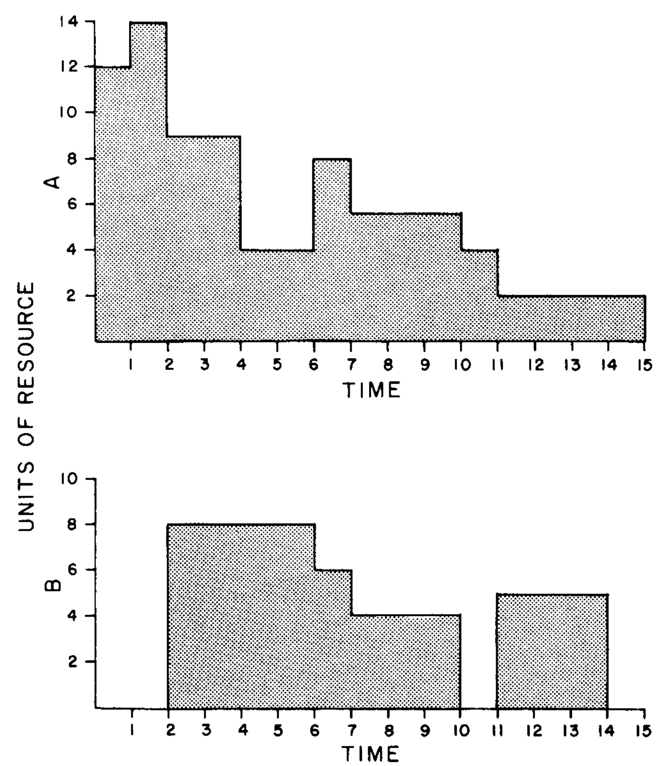

Figure 4--Amounts of resources required to complete the sample project *(fig. 1)* under the early start schedule *(fig. 3a)* fluctuate between time periods.

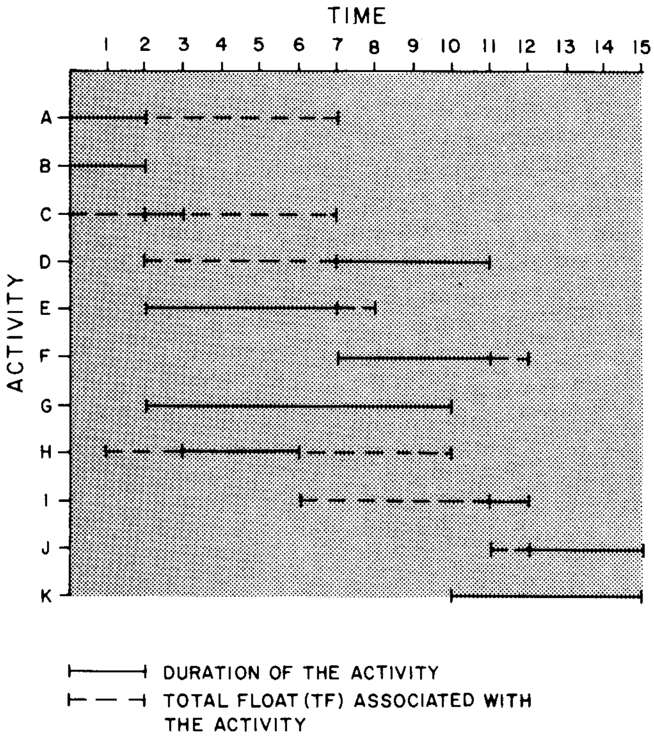

Figure 5--A schedule may not be desirable if it requires large quantities of resources during some time periods.

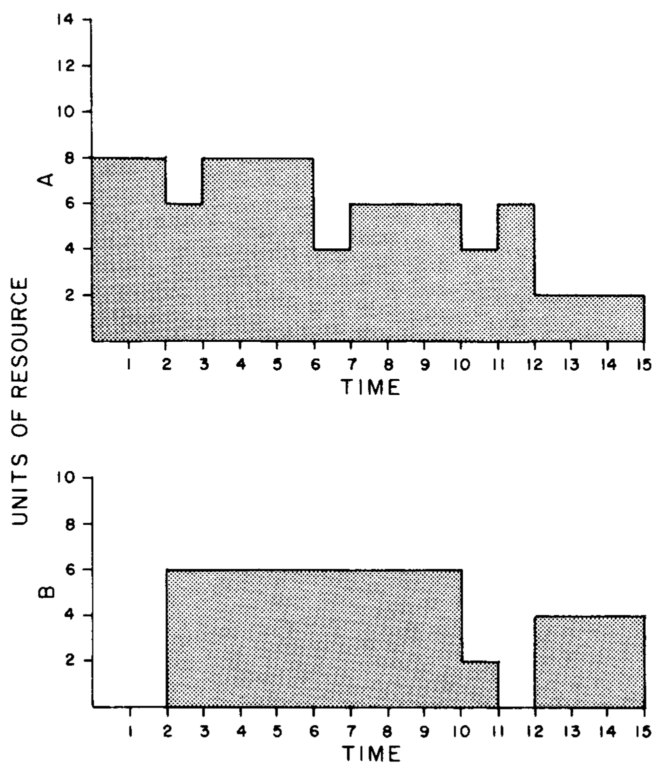

Figure 6--A schedule in which resource requirements are relatively level overtime is desired, because overhead costs of obtaining varied amounts of resources will be low.

The total amounts of resources needed for each time period of the project under the early start schedule of *table 1* would be as shown in *figure 4.*

If, at most, 10 units of resource A are available at any given time, then this schedule is of no use. On the other hand, if sufficient resources are available for this schedule, it still may not be desirable because of the large quantities of resources needed during some time periods. A better schedule would be one in which the amounts of resources needed are somewhat level, for then the overhead costs of obtaining varied amounts of resources are low. A better schedule would be that shown in *figure 5,* from which the amounts of resources needed are relatively level over time *(fig. 6).*

There is no natural or agreed-upon measure of optimality for resource schedules, and no known resource analysis technique will yield the best schedule because of the mathematical complexity involved. However, many heuristic routines find good schedules and are often used. A computer can be used to generate schedules between the early start (*fig. 3a*) and late start schedules (*fig. 3b*) to find a schedule (*fig. 5*) in which resource levels are relatively constant (*fig. 6*).

Cost Analysis

To further analyze possible schedules for a project, the project manager may use cost analysis. Cost analysis is the study of time-cost tradeoffs and of the corresponding possible schedules for a project, and is aimed at finding a project schedule for which the overall project cost is acceptable. The duration of many activities in a project may be shortened by adding more resources to the performance of the activity. That is, a time-cost tradeoff exists for many activities. Increasing the resources (and therefore the cost) spent on a few activities may decrease the time required to finish the project sooner and thereby reduce the overall cost of the project. Techniques of cost analysis differ, but for some projects none are feasible due to the complexities of time-cost calculations and indirect project costs.

FIRE ECONOMICS EVALUATION SYSTEM

The following broad subjective requirements were established to guide development of the CPM system for the FEES project:

- Ability to display selected activities of a small-to-medium project in a time-phased, event-keyed mode,
- Means of tracking interrelationships between project activities to provide information, such as the total slip in the project schedule resulting from a change in schedule of one activity or the change in the schedule of all activities caused by a change in schedule of one activity,

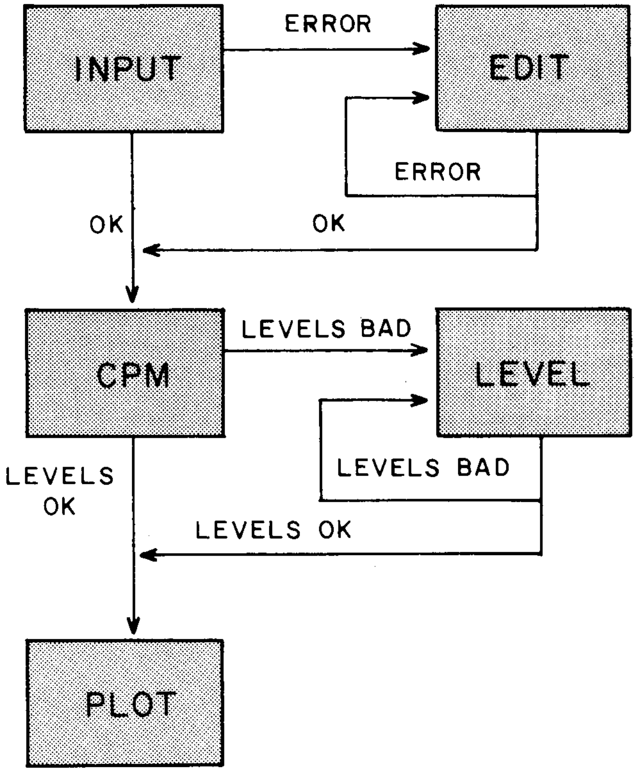

Figure 7--The computer programs (INPUT, EDIT, CPM, LEVEL, PLOT) in the routine developed for the Fire Economics Evaluation System are run in a natural order.

• Features such as operational flexibility and ease of update as a high priority.

The hardware available required that procedures developed had to run on an IBM 370 computer, accessed either through a DATA 100 card system or through a PRIME computer driven from interactive terminals. In reality, the PRIME computer served only as a front-end component to the IBM 370, similar to the DATA 100 card system. A30-inch CALCOMP Plotter could be accessed through the IBM 370 if plotted graphics output of the schedules generated was desired. The program was also to be written in FORTRAN. These constraints caused some difficulty in developing the CPM computer package. An additional complicating factor was that the package would be developed on the IBM 4341 computer at Pomona College and then transferred to the Forest Service's Forest Fire Laboratory at Riverside for final installation and checkout.

The CPM package that was developed consisted of five major interconnected components: INPUT, EDIT, CPM, LEVEL, and PLOT

INPUT allows for entering into the computer all data necessary for the CPM analysis of a project;

EDIT allows for changing the data in any way, without unnecessarily repeating unchanged data;

CPM performs all CPM calculations on the data (forward pass, backward pass, calculation of float times, and identification of critical activities), and produces complete information on three different schedules: early start, late start, and a third schedule with effort levels improved by an automatic leveling routine;

LEVEL allows further improvement of effort levels by altering any of the three schedules produced by CPM, one activity at a time;

PLOT graphically produces high quality bar charts of any chosen project schedule with full labeling, float and precedence indicators, and other aids to project management.

These programs are run in their natural order (*fig. 7*). For a new project, INPUT is used first to create the set of data. CPM may then operate directly on this data set, or EDIT may be used to modify the data before CPM is run. The output of CPM consists of three basic schedules and the labor requirements implied by each. PLOT may then be called to draw the bar chart for any of these schedules, or LEVEL may be used to create modified schedules before PLOT is asked to draw any of them. For projects with data sets that have been created previously, one may begin directly with EDIT or CPM and proceed as above. For projects with data sets that have been processed by CPM, one may begin directly with LEVEL or PLOT.

Comparing Schedules

The CPM package analyzed an example data set describing 47 activities for the FEES project (*table 3*) and initially produced three schedules:

• Early start, in which each activity begins at its earliest possible time;

• Late start, in which each activity begins at its latest possible time; and

• Automatic, in which the computer checks many randomly generated schedules and automatically selects one with the lowest sum of squares of the effort levels. (This is one reasonable measure of the "levelness" of the resource requirements of a schedule. A lower sum of squares indicates a more level schedule; constant effort levels produce a minimum sum of squares.)

The automatic and late schedules were similar in form, and both appeared more level than the early schedule. However, the late schedule appeared to offer the greatest choice of moves to decrease high effort levels (*tables 4, 5--table 5* is on page 12). The LEVEL program was then used to alter the late start schedule, one activity at a time, until a fourth schedule with more balanced levels of effort was reached. This is the optimized schedule *(tables 6, 7).*

Eleven activities were identified as critical to the FEES project:

CXXX	Develop Initial Attack Module
FXXX	Check Out Initial Attack Module
GXXX	Develop Fire Behavior Module
IIXX	Document Final Probability Model
KKXX	Document Final Fire Behavior Model
MMXX	Document Final Fire Behavior Module
OOXX	Document Final Cost Model
QQXX	Document Final Fire Effects Model
SSXX	Develop Large Fire Gaming Process
TTXX	Conduct Large Fire Gaming Exercises
UUXX	Prepare Final User Documentation

The automatic schedule left 4 activities at their early time, 12 at their latest, and 20 in between. The optimized schedule puts only 3 at early times, leaves 26 at late times, and only 7 in between.

The four schedules were compared on the basis of criteria related to the "levelness" of scientist efforts: sum of squares of individual efforts by month (converted to decimals), the maximum level of effort over the project, the number of scientist levels over 100 percent, the number of scientist levels equal to 0 percent, and the number of scientists who at some time have a level over 100 percent (*table 8*). Order of preference of the schedules is supported by each criterion. The optimized schedule is best in every one of the criteria compared.

Updating the Routine

Since the original development of the CPM network routine, a series of modifications have been made to simplify data manipulation, reduce running time, and to take advantage of equipment and executive software changes. The program has been used with updated activity information and has proved to be particularly helpful in determining critical activities that require management attention to achieve project objectives under restricted manpower allocation and reasonable time limitations.

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Table 3--*Forth-seven activities for the FEES project were analyzed with the CPM package*

Activity	Acronym	Duration (time units)	Scientist-months	Scientist initials	Precedences
Develop probability model	AXXX	6	4	FB	----
Collect C29 data base	BXXX	2	2	FB	----
Develop initial attack module	CXXX	6	4	PH	----
Collect arrival time information	DXXX	2	1	PH	----
Collect production rate information	EXXX	2	1	PH	----
Check out initial attack module	FXXX	2	2	PH	BXXX, CXXX, DXXX,EXXX
Develop fire behavior module	GXXX	6	4	LS	----
Develop detection size relationships	HXXX	2	2	LS	----
Collect detection size data	LXXX	2	1	LS	----
Obtain detection size results	JXXX	1	1	LS	AXXX, HXXX, IXXX, GXXX, JXXX
Check out fire behavior module	KXXX	1	1	LS	----
Develop fire effects module	LXXX	4	4	DP	----
Collect fire effects data	MXXX	4	2	DP	LXXX, MXXX
Obtain behavior/effects relationship	NXXX	2	2	DP	----
Develop cost module	OXXX	4	2	AG	----
Obtain per-unit cost data	PXXX	4	1	AG	----
Obtain mopup data	QXXX	4	1	AG	----
Develop cost/activity relationships	RXXX	2	2	AG	OXXX, PXXX, QXXX
Develop resource values	SXXX	4	1	TM	----
Develop net value change relationships	TXXX	4	1	TM	----
Integrate preliminary system	UXXX	2	2	FB	FXXX, KXXX, NXXX, RXXX, SXXX, TXXX
Verify results	VXXX	1	1	FB	UXXX
Collect Z12 data base	WXXX	2	1	FB	BXXX
Collect Z12 arrival information	XXXX	2	1	PH	DXXX
Collect Z12 production rate data	YXXX	2	1	PH	EXXX
Collect Z12 detection size data	ZXXX	2	2	LS	IXXX
Collect Z12 fire effects data	AAXX	4	2	DP	MXXX
Collect Z12 cost data	BBXX	2	1	AG	PXXX
Collect Z12 mopup data	CCXX	2	1	AG	QXXX
Develop Z12 resource values	DDXX	2	1	TM	SXXX
Modify preliminary system	EEXX	4	4	FB	VXXX
Integrate new data base	FFXX	2	1	FB	WXXX, XXXX, YXXX, ZXXX, AAXX, BBXX, CCXX, DDXX, EEXX
Verify results	GGXX	1	1	FB	FFXX, TTXX
Document probability model	HHXX	2	2	FB	VXXX
Document final probablity model	IIXX	2	2	FB	GGXX
Document fire behavior model	JJXX	2	2	LS	VXXX
Document final fire behavior	KKXX	2	2	LS	GGXX
Document initial attack module	LLXX	2	2	PH	VXXX
Document final fire behavior model	MMXX	2	2	PH	GGXX
Document cost model	NNXX	2	2	AG	VXXX
Document final cost model	OOXX	2	2	AG	FXXX
Document fire effects model	PPXX	2	2	DP	VXXX
Document final fire effects model	QQXX	2	2	DP	GGXX
Document resource values	RRXX	2	2	TM	GGXX
Develop large fire gaming process	SSXX	6	4	PH	FXXX
Conduct large fire gaming exercises	TTXX	6	6	PH	SSXX
Prepare final user documentation	UUXX	2	2	TM	IIXX, KKXX, MMXX, OOXX, QQXX

Table 4--*Late schedule for FEES project*

Activity[1]	Scientist's initials	Months[2]																								
		J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J
AXXX	FB	S[3]	S	S	D	D	D	D	D	D																
BXXX	FB	S	S	S	S	D	D																			
CXXX	PH	D	D	D	D	D	D																			
DXXX	PH	S	S	S	S	D	D																			
EXXX	PH	S	S	S	S	D	D																			
FXXX	PH							D	D																	
GXXX	LS	S	S	S	S	D	D	D	D	D	D															
HXXX	LS	S	S	S	S	S	S	S	D	D																
IXXX	LS	S	S	S	S	S	S	S	D	D																
JXXX	LS							T	T	T	D															
KXXX	LS								T	T	T	D														
LXXX	DP	S	S	S	S	S	D	D	D	D																
MXXX	DP	S	S	S	S	S	D	D	D	D																
NXXX	DP					T	T	T	T	T	D	D														
OXXX	AG	S	S	S	S	S	D	D	D	D																
PXXX	AG	S	S	S	S	S	D	D	D	D																
QXXX	AG	S	S	S	S	S	D	D	D	D																
RXXX	AG					T	T	T	T	T	D	D														
SXXX	TM	S	S	S	S	S	S	S	D	D	D	D														
TXXX	TM	S	S	S	S	S	S	S	D	D	D	D														
UXXX	FB									T	T	T	D	D												
VXXX	FB											T	T	T	D											
WXXX	FB			T	T	T	T	S	S	S	S	S	S	S	S	S	S	D	D							
XXXX	PH			T	T	T	T	S	S	S	S	S	S	S	S	S	S	D	D							
YXXX	PH			T	T	T	T	S	S	S	S	S	S	S	S	S	S	D	D							
ZXXX	LS			T	T	T	T	T	T	T	S	S	S	S	S	S	S	D	D							
AAXX	DP					T	T	T	T	T	S	S	S	S	S	D	D	D	D							
BBXX	AG					T	T	T	T	T	S	S	S	S	S	S	S	D	D							
CCXX	AG					T	T	T	T	T	S	S	S	S	S	S	S	D	D							
DDXX	TM					T	T	T	T	T	T	T	S	S	S	S	S	D	D							
EEXX	FB												T	T	T	D	D	D	D							
FFXX	FB																T	T	T	D	D					
GGXX	FB																					D				
HHXX	FB												T	T	T	S	S	S	S	S	S	S	S	S	D	D
IIXX	FB																						D	D		
JJXX	LS												T	T	T	S	S	S	S	S	S	S	S	S	D	D
KKXX	LS																						D	D		
LLXX	PH												T	T	T	S	S	S	S	S	S	S	S	S	D	D
MMXX	PH																						D	D		
NNXX	AG												T	T	T	S	S	S	S	S	S	S	S	S	D	D
OOXX	AG																						D	D		
PPXX	DP												T	T	T	S	S	S	S	S	S	S	S	S	D	D
QQXX	DP																						D	D		
RRXX	TM																						S	S	D	D
SSXX	PH									D	D	D	D	D	D											
TTXX	PH															D	D	D	D	D	D					
UUXX	TM																								D	D

[1]See *table 3* for explanations of acronyms.

[2]Letters represent months beginning with July.

[3]S represents the period of safety float in which the activity may be moved up without affecting any preceding activity (and hence occurs only before the scheduled period). D represents the schedule period of performance of an activity. T represents the additional period of total float in which the activity may be moved earlier or later without affecting the overall project time, but possibly affecting activities that precede or follow it. F represents the period of free float, in which the activity may be delayed without affecting any following activity (and hence occurs only after the scheduled period.)

Table 6-Optimized schedule *for FEES project*[1]

Activity	Scientist's initials	Months																								
		J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J
AXXX	FB	S	S	S	D	D	D	D	D	D																
BXXX	FB	D	D	T	T	T	T																			
CXXX	PH	D	D	D	D	D	D																			
DXXX	PH	S	S	D	D	T	T																			
EXXX	PH	S	S	S	S	D	D																			
FXXX	PH							D	D																	
GXXX	LS	S	S	S	D	D	D	D	D	D	T															
HXXX	LS	S	D	D	F	F	F	T	T	T																
IXXX	LS	D	D	T	T	T	T	T	T	T																
JXXX	LS							T	T	T	D															
KXXX	LS								T	T	T	D														
LXXX	DP	S	D	D	D	D	T	T	T	T																
MXXX	DP	S	S	S	S	S	D	D	D	D																
NXXX	DP					T	T	T	T	T	D	D														
OXXX	AG	S	S	S	S	S	D	D	D	D																
PXXX	AG	S	S	S	S	S	D	D	D	D																
QXXX	AG	S	S	S	S	S	D	D	D	D																
RXXX	AG					T	T	T	T	T	D	D														
SXXX	TM	S	S	S	S	S	S	S	D	D	D	D														
TXXX	TM	S	S	S	S	S	S	S	D	D	D	D														
UXXX	FB								T	T	T	D	D													
VXXX	FB										T	T	T	D												
WXXX	FB			T	T	T	T	S	S	S	D	D	F	F	F	F	T	T	T							
XXXX	PH			T	T	T	T	S	S	S	S	S	S	D	D	F	T	T	T							
YXXX	PH			T	T	T	T	S	S	S	S	D	D	F	F	F	T	T	T							
ZXXX	LS			T	T	T	T	T	T	T	S	S	S	S	S	S	S	D	D							
AAXX	DP					T	T	T	T	T	S	S	S	S	S	D	D	D	D							
BBXX	AG					T	T	T	T	T	S	S	S	S	S	S	S	D	D							
CCXX	AG					T	T	T	T	T	S	S	S	S	S	S	S	D	D							
DDXX	TM					T	T	T	T	T	T	T	S	S	S	S	S	D	D							
EEXX	FB												T	T	T	D	D	D	D							
FFXX	FB																T	T	T	D	D					
GGXX	FB																					D				
HHXX	FB												T	T	T	S	S	S	S	S	S	S	S	S	D	D
IIXX	FB																						D	D		
JJXX	LS												T	T	T	S	S	S	S	S	S	S	S	S	D	D
KKXX	LS																						D	D		
LLXX	PH												T	T	T	S	S	S	S	S	S	S	S	S	D	D
MMXX	PH																						D	D		
NNXX	AG												T	T	T	S	S	S	S	S	S	S	S	S	D	D
OOXX	AG																						D	D		
PPXX	DP												T	T	T	S	S	S	S	S	S	S	S	S	D	D
QQXX	DP																						D	D		
RRXX	TM																						D	D	F	F
SSXX	PH									D	D	D	D	D	D											
TTXX	PH															D	D	D	D	D	D					
UUXX	TM																								D	D

[1]See *table 3* for explanation of terms.

Table 5--*Levels of effort for late schedule for FEES project* (table 4), *by scientist's initials and month*

Month	FB	PH	LS	DP	AG	TM
	Percent per month					
J	0	66	0	0	0	0
A	0	66	0	0	0	0
S	0	66	0	0	0	0
O	66	66	0	0	0	0
N	166	166	66	0	0	0
D	166	166	66	150	100	0
J	66	100	66	150	100	0
F	66	100	216	150	100	50
M	66	66	216	150	100	50
A	0	66	166	100	100	50
M	0	66	100	100	100	50
J	100	66	0	0	0	0
J	100	66	0	0	0	0
A	100	66	0	0	0	0
S	100	100	0	50	0	0
0	100	100	0	50	0	0
N	150	200	100	50	100	50
D	150	200	100	50	100	50
J	50	100	0	0	0	0
F	50	100	0	0	0	0
M	100	0	0	0	0	0
A	100	100	100	100	100	0
M	100	100	100	100	100	0
J	100	100	100	100	100	200
J	100	100	100	100	100	200

Table 7--*Levels of effort for optimized schedule for FEES project* (table 6), *by scientist's initials and month*

Month	FB	PH	LS	DP	AG	TM
	Percent per month					
J	100	66	50	0	0	0
A	100	66	150	100	0	0
S	0	116	100	100	0	0
0	66	116	66	100	0	0
N	66	116	66	100	0	0
D	66	116	66	50	100	0
J	66	100	66	50	100	0
F	66	100	66	50	100	50
M	66	66	66	50	100	50
A	50	66	100	100	100	50
M	50	116	100	100	100	50
J	100	116	0	0	0	0
J	100	116	0	0	0	0
A	100	116	0	0	0	0
S	100	100	0	50	0	0
0	100	100	0	50	0	0
N	100	100	100	50	100	50
D	100	100	100	50	100	50
J	50	100	0	0	0	0
F	50	100	0	0	0	0
M	100	0	0	0	0	0
A	100	100	100	100	100	100
M	100	100	100	100	100	100
J	100	100	100	100	100	100
J	100	100	100	100	100	100

Table 8--*Possible schedules for FEES project, by various measures of "levelness"*

Schedule	Sum of squares	Maximum level	Levels over 100 pct	Levels equal to 0	Scientists over 100 pct
Earls	115.93	216	24	66	5
Late	108.01	216	17	59	5
Automatic	94.39	200	15	47	4
Optimized	85.73	150	9	45	2

Anderson, Earl B.; Hales, R. Stanton. **Critical path method applied to research project planning: Fire Economics Evaluation System (FEES).** Gen. Tech. Rep. PSW-93. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1986. 12 p.

The critical path method (CPM) of network analysis (a) depicts precedence among the many activities in a project by a network diagram; (b) identifies critical activities by calculating their starting, finishing, and float times; and (c) displays possible schedules by constructing time charts. CPM was applied to the development of the Forest Service's Fire Economics Evaluation System (FEES)--a simulation model for evaluating fire program options. A computerized CPM package analyzed 47 activities, and produced basic schedules and labor required for each. One program in the package was used to alter a basic schedule to produce one that required less variable levels of labor. The CPM approach can be applied to a variety of resource management and other forestry-related projects.

Retrieval Terms: research planning, CPM, PERT, project scheduling

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