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Title ANALYSIS OF HUMAN AND EQUIPMENT PERFORMANCE IN CRITICAL PATH SCHEDULING

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The utilization of historical data is suggested as an approach to solving some of the difficulties involved in the estimating of activity durations in critical path scheduling.

The historical data presented show the effects of various weather conditions upon the performance of human labor and mechanical equipment. When combined with climatological data for a particular locality, it becomes possible to use the historical data to estimate the degree of performance by humans and mechanical equipment that is most likely to be expected during that interval of time.

The concept of a probability-performance calendar is developed along with a nomograph for relating the degree of performance to the estimated optimistic time to obtain the most likely time estimate for the activity. Finally, it is shown how the historic data is applied in the critical path analysis by means of comparing the use of the proposed approach to estimating activity durations with the critical path analysis of an actual project.

ANALYSIS OF HUMAN AND EQUIPMENT PERFORMANCE IN CRITICAL PATH SCHEDULING

by

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The author is also indebted to Professors W. F. Engesser, and to the many contractors and construction superintendents who supplied time and information so that the data represented in this thesis can be of practical value. Special thanks must go to Mr. Petriquin for supplying the information and example used to test the many assumptions and data presented in this thesis.

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ANALYSIS OF HUMAN AND EQUIPMENT PERFORMANCE IN CRITICAL PATH SCHEDULING

I. INTRODUCTION

> Lacking a way of forecasting the future with complete accuracy, planning at least attempts to anticipate possible futures and their effects on achieving desired goals (21, p. 6).

Project schedules of many kinds can be represented as directed networks in which the activities of a project correspond to segments in the network. The structure of the network represents the order in which these activities may be performed; the duration of the project being the longest cumulative path through the network. If activity durations are known with certainty, finding the longest, or critical, path is not difficult, even for very large projects. However, for most projects the estimated activity durations are highly uncertain. It is possible, then, to find that the predetermined critical path and the actual critical path may not be the same.

There are two fundamental approaches to estimating activity duration. This has resulted in two closely related families of network analysis systems: PERT (Program Evaluation and Review Techniques) related systems employing statistical techniques for estimating activity durations (7; 22; 23); CPS (Critical Path Scheduling) related systems which assume a deterministic activity duration estimate based upon prior experience and knowledge of the activity (15; 17; 22).

PERT systems are more commonly associated with the scheduling of research and development projects, whereas CPS systems have been primarily adopted for use by the construction industry.

The use of either PERT or CPS systems does not necessarily preclude the possibility of introducing new techniques to be used in conjunction with the estimating of activity durations. The uncertainties that affect the estimated activity durations present a challenging area of study. All activities in the PERT or CPS analysis are affected to varying degrees by external factors. Factors such as the number of possible work days in a year remain constant. However, the number of actual work days are dependent on strikes, weather phenomena, and other factors with characteristic random distributions since they influence the activity durations.

To study all facets of the factors which produce uncertainties in the estimated activity durations would be an almost unlimited task. For this reason, and due to its importance to the construction industry, this thesis will be restricted to a study of the effects of weather phenomena on human and equipment performance. The techniques and methods of analysis are applicable for the analysis of other random factors that affect human and equipment performance.

The purpose of this study, then, is to characterize qualitative aspects of individual networks, to determine whether the assumption of deterministic activity durations is adequate, and to attempt to estimate the magnitude of the errors involved with this assumption with a final goal of determining an improved method for estimating activity durations.

Planning

Planning is the establishing of goals, policies, and procedures for determining future courses of action. Through planning an attempt is made to anticipate possible futures and their effect on achieving desired goals. Since CPS is used as an aid in planning, consideration should be given to the various degrees of planning.

There are four distinct concepts of planning as follows:

> Certainty, the assumption that there is only one possible future course of action, that the future is predetermined and that it is known. Any other possible futures are suppressed in favor of the single value estimation.
>
> Risk, the assumption that the absolute future is unknown, but that there are several futures with which estimated probabilities may be associated.
>
> Uncertainty, the presence of a variety of futures is evident, but due to a lack of information it is not feasible to make specific assumptions about their probabilities.
>
> Ignorance, the basing of decisions more on emotional response than upon a rational decision, or a refusal to acknowledge the possibilities of varied future occurrences.

The ultimate level of planning, certainty, which is assumed in the critical path analysis should theoretically result in a schedule that is capable of being completed, as stated, 100 percent of the time. For many activities, certainty may be a reasonable assumption since the activity durations are relatively short in duration with only a small probability of being affected by outside factors. However, the reliance upon past experience in estimating activity durations suggests that there are conditions present which affect activity durations to an extent that is not readily determined by the uninitiated analyst.

Experience is developed only by close contact to the actual performance of the activities that are being scheduled. Familiarity with the factors that cause delays is obtained through the repetition of activities under a variety of external conditions. With experience, the level of planning is increased to that of uncertainty.

Uncertainty utilizes the information obtained from experience only to the extent that it recognizes that there are external factors to be considered in the scheduling process. An attempt to do any more than make general allowances in the schedule for any contingencies which may arise is not recognized as feasible or practical at this level of planning. Unfortunately, it is at this level that the planning required in the critical path analysis is generally terminated. The assumption of certainty enters at this level to avoid a more lengthy or involved analysis of the proposed schedule. When it is eventually realized that the schedule cannot be adhered to, CPS is condemned as being too idealized or impractical, whereas the actual difficulty may reside in the original estimated times for activity durations.

There are two problems that must be considered before the level of risk can be obtained. The first is that of defining the factors which cause delays in activity durations. Such a list would not only include weather, but must include strikes, logistics, the attitude of the company performing the work, and many other factors. Once the factors have been determined which are pertinent to a particular category of activities, then a statistical study must be made to determine the characteristics of the factors and the extent to which they affect the activity durations. This is not an easy task, but when once accomplished for one project, it would be possible to extend the use of this knowledge to many other projects.

The most desirable level of planning, that of certainty, is the level which will probably never be achieved. To do so would enable the user of the analysis to predetermine the requirements of men and equipment and would thus provide a means of most effectively using the resources at his command. The best that can be hoped for is its approximation through the refinement of the level of planning, risk, similar to that approached in production planning for highly mechanized processes.

CPS

An efficient control over the three elements: limited resources, cost, and time, is required in the operation of any profit making enterprise. Fortunately, there is a science associated with each one of these elements. Figure I-1 expresses these relationships in an orthogonal system. Cost and profits are seen to be the subject of economics, whereas the optimum utilization of time is studied in management science.

Considered separately, these sciences present only a fraction of their total possible benefit to an enterprise. The best utilization of one axis of the orthogonal system is hardly adequate for effective decision making unless other axes, or dimensions, are also taken into account.

Several techniques have been developed to analyze two-dimensional problems. The development of linear programming is closely associated with that of economic theory (14, p. 365-367) and is used in the analysis of problems involving both cost and limited resources. In general, there are a large number of items to be distributed in a variety of ways. These may be materials, men, or equipment. Constraints may be applied. For example, some or all materials may be available in a limited quantity, or there may be a limited supply of manpower available. Under these constraints, there is usually a

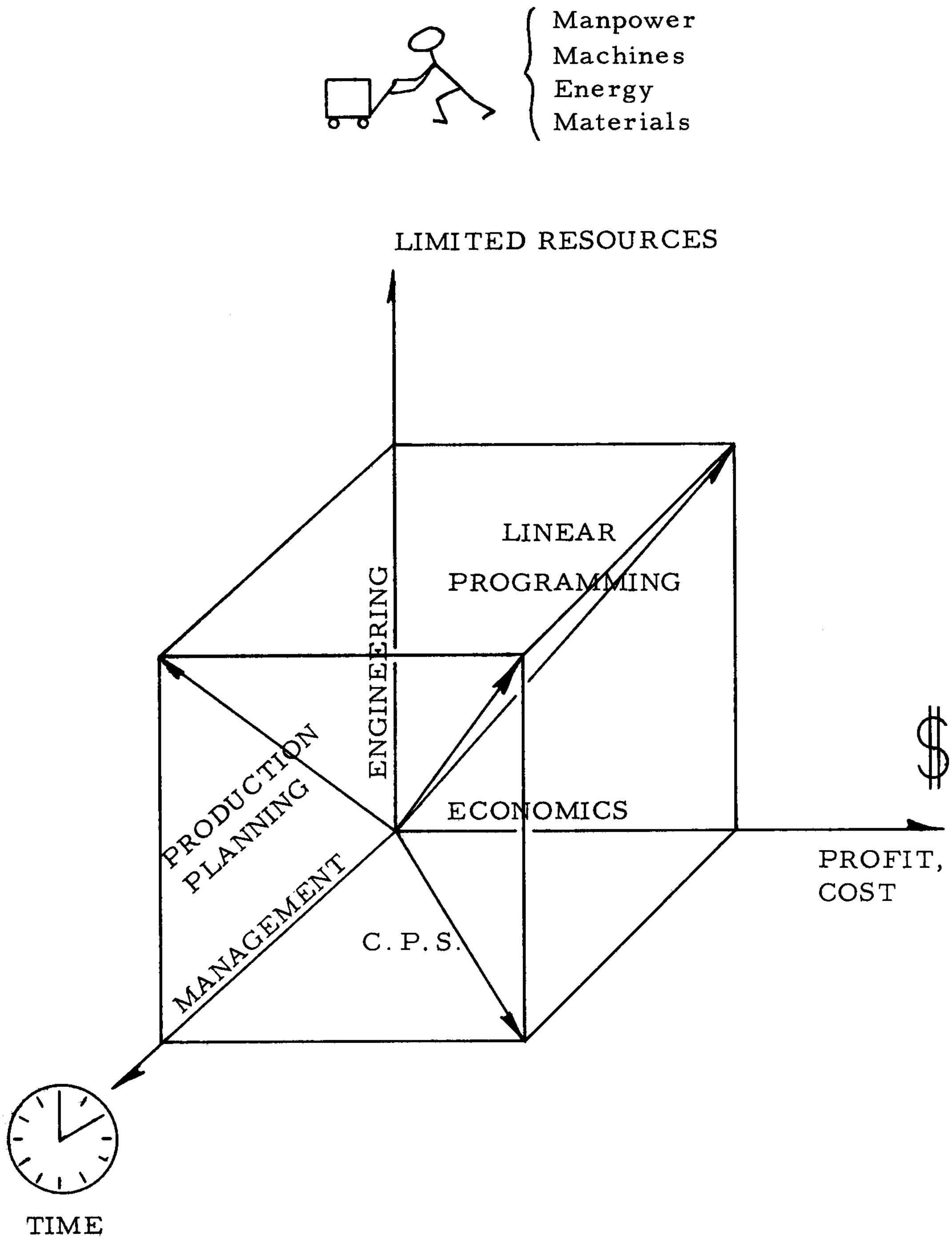


Figure I-1. Industrial system (17, p. 4).

cost or profit function to be minimized or maximized.

The relationship between limited resources and time is explored in production planning and control. Production planning involves setting production levels for several periods in the future and assigning general responsibility to provide data for making decisions on the size and composition of the labor force, capital, equipment, and plant additions. Production control involves the constant readjustment of plans and schedules in the light of collecting operating facts (6, p. 3-4).

The application of linear programming and production planning makes possible a two-dimensional analysis of limited resources and time. The remaining two dimensions, time-cost, are related by the techniques of critical path scheduling. Therefore, critical path scheduling may be defined as:

> Critical Path Scheduling is a management control tool for defining, integrating, and analysing what must be done to complete a project economically and on time (22, p. 1).

Efforts have been made to expand CPS to include limited resources. Manpower leveling, equipment allocation, and job assignments are only a few of the problems in which CPS is finding an increasing application.

Elements of CPS

A project planned and carried out under human supervision is composed of an intricate alternation of "activities" and "events." The activities are time consuming efforts which occur between two events. An event, then, is an instant in time which may be regarded as a point of accomplishment of all previous activities and a moment of decision to start a new activity.

In a CPS analysis it is first necessary to determine a list of activities involved in the project. This is popularly known as an "activity list." Table I-1 is an activity list for a small patio construction project (21, p. 7). Included in the activity list is the estimated duration for each activity, as well as the symbol used to represent the activity in the schematic of the network.

The relationships between the activities must also be defined. When one activity must be completed before a second activity can begin, the first is considered to be a restraint on the second. The symbol (A>B) indicates that activity A is a restriction on B. All restrictions in a network can be defined by means of a restriction list similar to the one in Table I-2. The first activity is also referred to as a "prerequisite" to any subsequent activities and the latter are referred to as "postrequisites" with respect to any prior activities.

Table I-1. Activity list.

Symbol	Activity	Estimated Time - hr.
A	Order and deliver lumber, Fiberglas, nails, etc.	2
B	Order and deliver concrete blocks, mortar, etc.	2
C	Excavate for foundation	10
D	Erect block foundation	6
E	Frame roof and deck	8
F	Lay decking	6
G	Place roofing	2
H	Clean up	2
I	Erect cement block windbreak	6

Table I-2. Restriction list.

A>E	D>E	G>H
B>D, I	E>F, G	I >H
C>D	F>H	

An "arrow network" can be constructed from the information contained in the activity list and the restriction list. The arrow network is a graphical representation of the sequence of activities required to complete a project. Time flows from left to right, but the arrows, representing individual activities, are dimensionless.

There frequently occurs in the critical path analysis a restraint relationship which requires no time but establishes a restriction. This is a "dummy" activity which is represented by a dotted arrow drawn from the head of the prerequisite activity to the tail of the restricted activity.

The arrow network constructed from the data in Tables I-1 and I-2 is shown in Figure I-2.

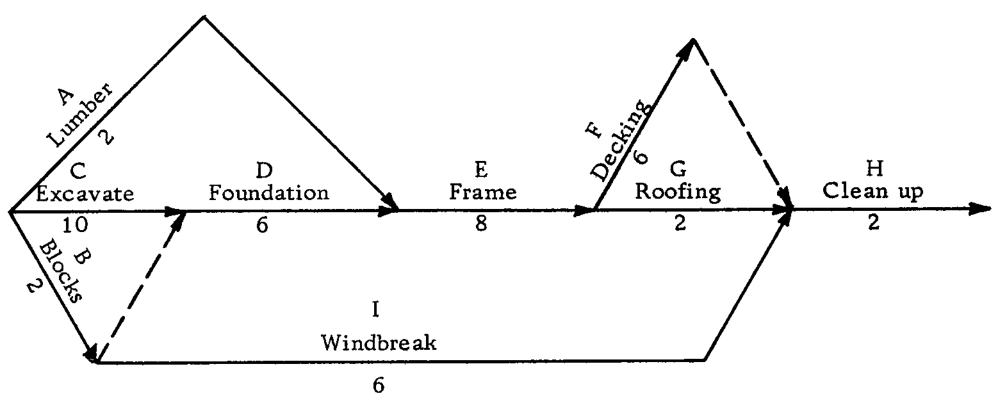


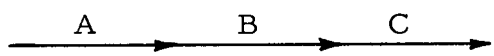
Figure I-2. Arrow network for patio construction project.

Another useful concept in critical path analysis has been described in a thesis by Michael Inoue of Oregon State University (17, p. 24). Closely related to the concepts of "prerequisites" and "postrequisites" are the concepts of "antecedents" and "predecessors." These terms are defined as follows:

> Prerequisite: An activity A is said to be a prerequisite of another activity B if and only if the termination of A is a direct requirement for the initiation of B. This relationship can be symbolically expressed as A-B and graphically shown as:

> Postrequisite: If an activity A is a prerequisite to another activity B, then activity B is said to be a postrequisite of A. This may be written as A-B or B-A and graphically shown in the same form as above.

> Descendent: An activity C is said to be a descendent of activity A if the termination of A is either directly or indirectly necessary for the initiation of C. Thus, if A-B and B-C, both B and C are descendants of A, but only B is a postrequisite of A.



> Antecedent: By the same token, A is said to be an antecedent of C when C is a descendant of A. Thus, all prerequisites of C are antecedents of C, but not all antecedents are prerequisites of C.

The next phase of the critical path analysis involves a time analysis of the activities.

Time Analysis

The heart of CPS, or any other scheduling system, is in its ability to adequately estimate the activity durations. The activity durations are usually listed with the activity descriptions, as in

Table I-1. From the estimated activity durations and the activity restriction list, it is possible to calculate the Earliest Start (ES) and Latest Start (LS) times and the Earliest Finish (EF) and Latest Finish (LF) times for each activity.

The Earliest Start and Earliest Finish times are related by:

$$EF = ES + ET \qquad \text{(eq. I-1)}$$

where ET represents the Estimated Time for the activity duration.

A similar relation exists between the Latest Start and the Latest Finish:

$$LF = LS + ET \qquad \text{(eq. I-2)}$$

The accumulative method for determining the ES and LF values is described in "A Working Manual for Critical Path Scheduling" by J. L. Riggs and C. O. Heath (22, p. 41). First, the EF times are determined for all the activities originating from a given event. The largest time values are the ES times for the next activities. Eq. I-1 is then used to compute the EF. This process is repeated until all the earliest times have been determined. The project end date is used as the LF of the final activity. The reverse process is then performed to determine the smallest LS of all the postrequisite activities as LF, alternated with the application of eq. I-2 to determine all the latest times.

There are two other time values of interest: Total Float, the surplus time available to an activity without causing the delay of an activity on the critical path, and Free Float, the surplus time available to an activity without affecting the earliest start time of any other activity. Total float can be expressed as the difference between the latest and earliest time values:

$$TF = LS - ES = LF - EF \qquad \text{(eq. I-3)}$$

Time Chart

After all the time values have been calculated, a graphical presentation using a time scale can be derived. This is known as a Time Chart. The time chart has a one to one correspondence to an arrow network. Dotted lines are used to express either a dummy activity or the float portion of an activity. A solid horizontal line denotes the job portion of an activity. A solid vertical line indicates an event, with all prerequisites connected to the left and all postrequisites connected to the right. The time scale always increases from left to right. An arrow is used to indicate a dummy, much the same way as it did in the arrow network.

The correspondence between an arrow network and a time chart is shown on Figure I-3.

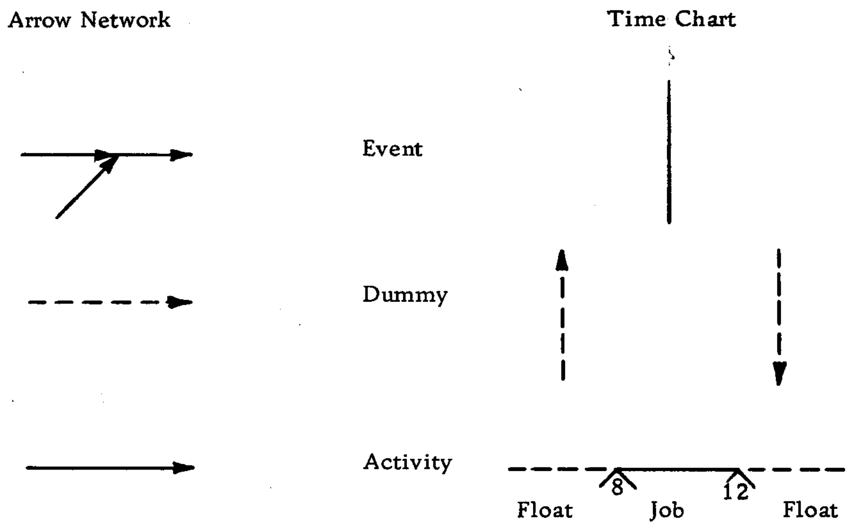


Figure I-3. Graphic symbols.

Figure I-4 is an example of a time chart based upon the data for the patio construction project example problem.

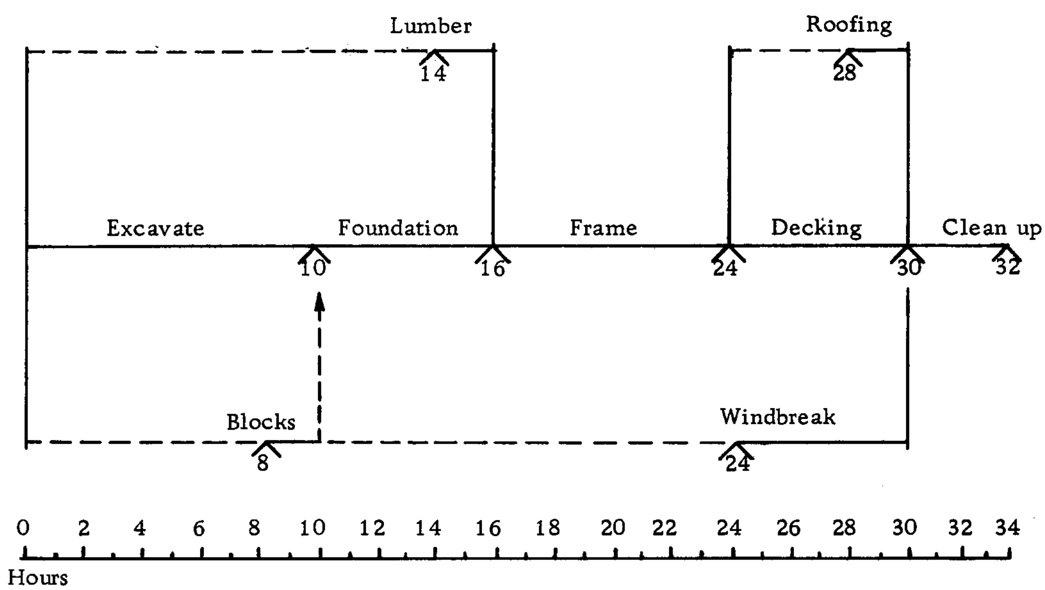


Figure I-4. Time chart for patio construction project.

With this brief review in critical path terminology, we now turn to an investigation of the effects of weather on human and equipment performance in the construction industry.

II. HUMAN BIOMETEOROLOGY

> Biometeorology is the investigation of the effects of the atmosphere on living organisms and the reactions and adjustments made by organisms in the atmosphere (11, p. 69).

There are upper and lower environmental limits in which human beings are capable of effectively performing mental and physical tasks. Many tests have been conducted to determine these limits, but only a few are of value to this report. Of primary interest are studies conducted by Clarke (9, p. 2) on the effects of low temperatures to hand reactions, the effects of heat and humidity on human performance, as determined by the Armored Medical Research Laboratory, and the Effective Temperature index as determined by the A.S.H.R.A.E. Research Laboratories.

Effects of Cold on Manual Dexterity

The effects of exposure to cold temperatures on the manual performance of hands was the subject of a study conducted by Clarke. It was desired by Clarke to determine a lower temperature limit for unaffected manual performance of the hands. The hands of 12 men were cooled to skin surface temperatures of 55 F and 60 F on different experimental days. Performance times to complete a standard knot tying test were recorded when the subjects' hands first reached the appropriate hand skin temperature (HST); after 20 minutes of exposure to the criterion temperature, again after 40 minutes of exposure, and, finally, after 60 minutes exposure.

It was noted that human performance was sharply reduced when the hand skin temperature fell to 55 F and that the performance decrements at this skin temperature were increasing exponential functions of duration to exposure. In contrast, performance at 60 F hand skin temperature remained unaffected throughout the exposure period. In Figure II-1 the changes in manual performance of the hands are plotted as a function of HST and the duration of cold exposure for each temperature. The cooling of the hands was accomplished by exposing the subjects' hands to 10 F air within a refrigerated box. The rest of the body was exposed to a constant ambient temperature of 70 F and a relative humidity of 50 percent.

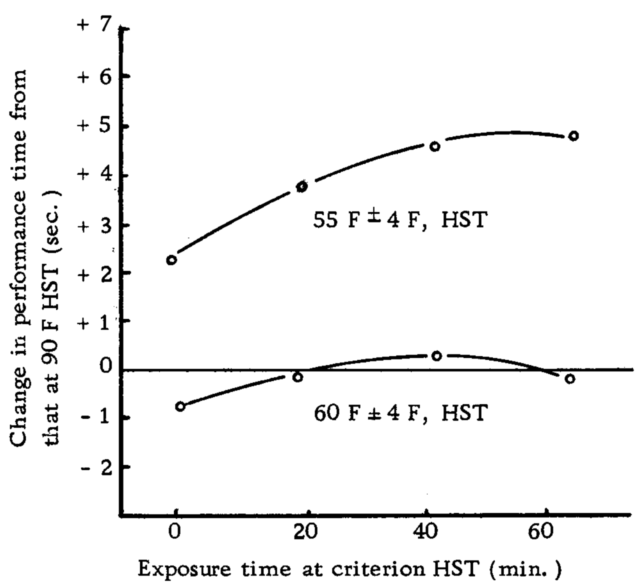


Figure II-1. Limiting hand skin temperature for unaffected manual performance in the cold (9, p. 4).

The Effects of Heat and Humidity on Human Performance

Cold may be the primary limiting factor to human performance during the winter, but during the summer months the heat and humidity may be the limiting factors, particularly where there is a great amount of energy expended in performing physical tasks. Among the forerunners in testing the effects of heat on human performance is the American Society of Heating, Refrigeration, and Air Conditioning Engineers Research Laboratories. Table II-1 summarizes the results of one series of tests designed to determine the physiological effects of men performing physical tasks at various effective temperatures. The effective temperature is an empirically derived index relating the effects of temperature and humidity on the sensation of warmth or cold felt by the human body.

Table II-1 shows that as the effective temperature increases, the actual work accomplished, in ft-lb, decreases rapidly, while at the same time there is a rapid rise in body temperature, pulse rate, and an increase in the loss of body weight due to increased perspiration (1, p. 116).

A study at the Armored Medical Research Laboratory (11, p. 72) was conducted to determine the upper limits of relative humidity and dry bulb temperature under which humans can perform physical work. Thirteen enlisted men were used as test subjects. During the tests

Table II-1. Physiological response to heat and humidity of men at work (1, p. 117).

Effective Temperature	Men at Work 90,000 Ft-Lb of Work per Hour			
	Actual Work Accomplished (Ft-Lb)	Rise in Body Temperature (°F per Hr)	Increase in Pulse Rate (Beats per Min per Hr)	Approximate Loss in Body Wt. by Perspiration (Lb per Hr)
60	225,000	0.0	6	0.5
70	225,000	0.1	7	0.6
80	209,000	0.3	11	0.8
85	190,000	0.6	17	1.1
90	153,000	1.2	31	1.5
95	102,000	2.3	61	2.0
100	67,000	4.0[a]	103[a]	2.7[a]
105	49,000	6.0[a]	158[a]	3.5[a]
110	37,000	8.5[a]	237[a]	4.4[a]

[a]Computed value from exposures lasting less than one hour.

these men were required to march for four hours at a rate of 3 mph while carrying 20 pound sacks. A wide range of environmental conditions rated as easy, difficult, and impossible were selected based upon the physiological reactions of the men at the end of the four hour period. The final results are reproduced in Figure II-2. At a dry bulb temperature of 96.5 F and 100 percent relative humidity, human performance was found to be almost impossible. As the humidity decreases, the temperature at which physical performance is possible rises to a temperature of 120 F at 38 percent relative humidity.

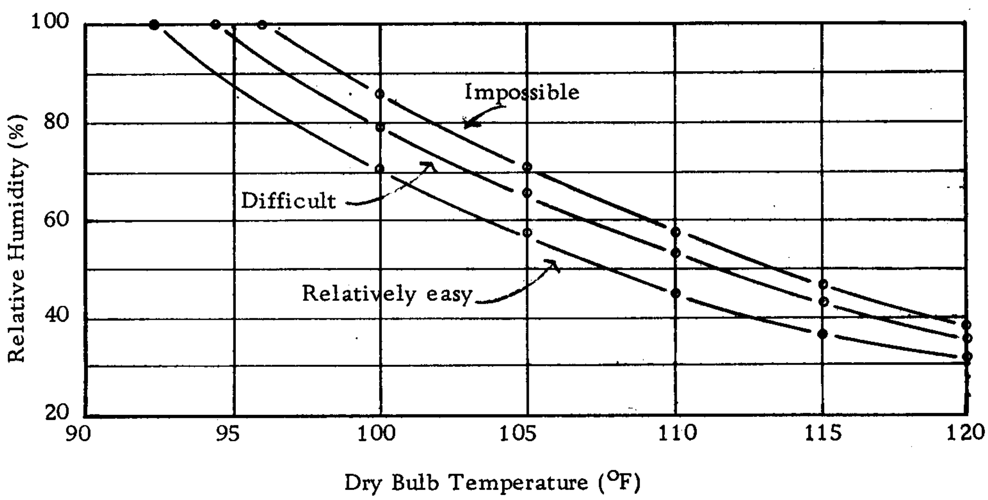


Figure II-2. Human humidity-temperature tolerance limits (11, p. 73).

Effective Temperature

Many composite indexes have been derived to relate various weather phenomena. One of the most noted is the Effective Temperature Index by the American Society of Heating, Refrigeration, and Air Conditioning Engineers. Trained subjects were used to compare the relative warmth of rooms by moving back and forth from one to the other. The numerical value of the Effective Temperature Index was determined by comparing the temperature of slowly moving 15 to 25 fpm) saturated air which produced a similar sensation to cold or warmth as the air to which it was being compared (2, p. 117).

The Effective Temperature Index is reproduced in Figure II-3.

Human Efficiency - Weather Correlation

Correlation of the studies by Clarke, the Effective Temperature Index, The Windchill Index (12, p. 435), and other reports pertaining to the effects of the environment on human performance, can be used as the foundation for a three-dimensional model to aid in the evaluation of human performance under various weather conditions. To relate these studies to the conditions encountered during construction work, 15 contractors and project superintendents in Montana and Oregon were invited to participate in a study to determine human production and equipment performance under a variety of weather

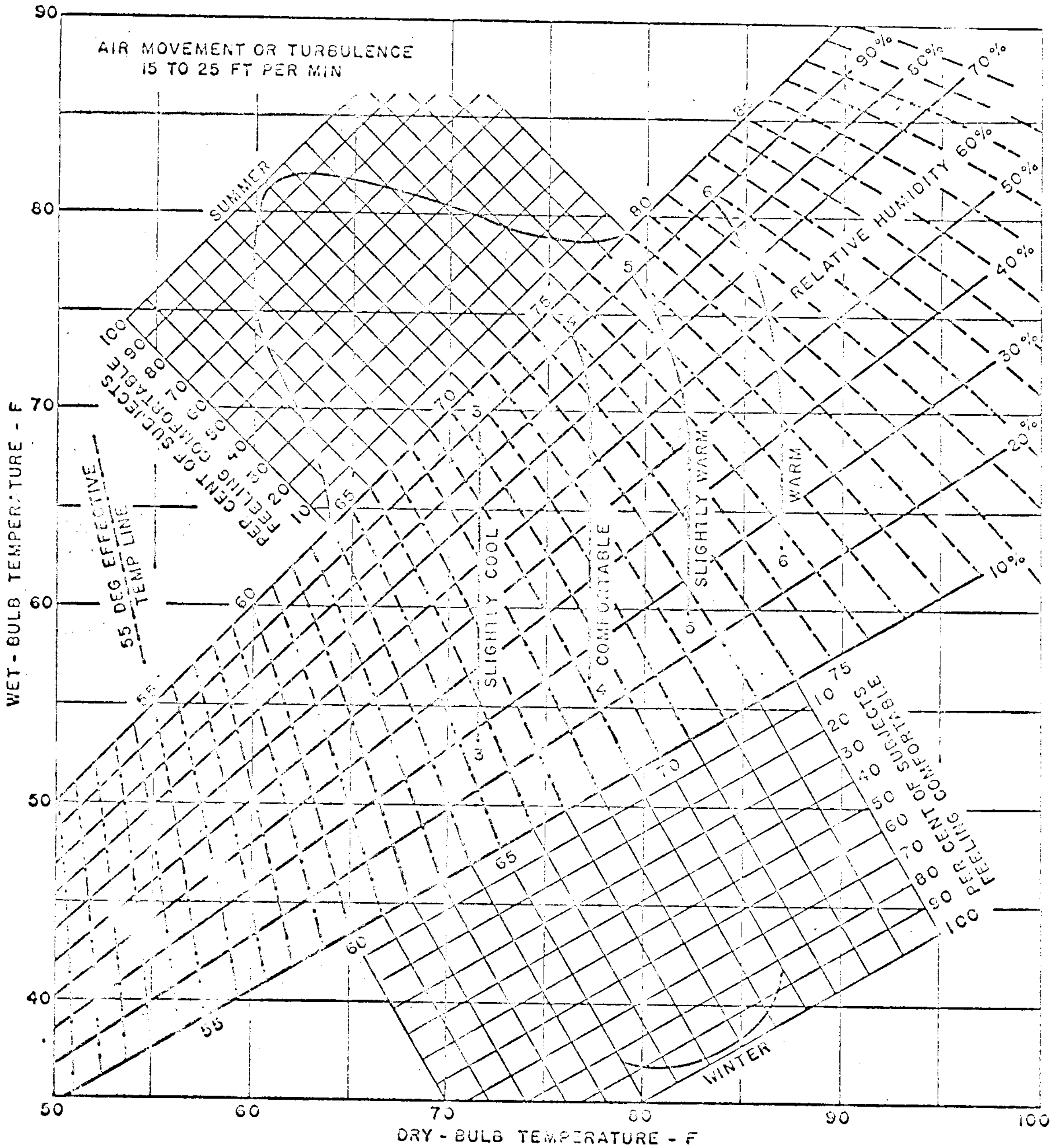


Figure II-3. Effective Temperature Index (7, p. 117).

conditions. These sessions were conducted at project sites, thus making it possible to observe the effects of a variety of weather conditions, from sub-zero temperatures to optimal, on a wide variety of construction activities.

The information obtained from on-the-job observations takes into consideration the need for construction laborers to wear protective clothing. It is assumed that the efficiency ratings developed compensate for such items as gloves, jackets, hats, and other apparel typical of that normally worn by laborers in various trades.

The relationship between effective temperature and the efficiency to be anticipated by construction laborers is closely approximated by the distribution in Figure II-4. Although this distribution is not exact for all construction activities, it does show that an acceptable level of efficiency is maintained when the effective temperature is in the range of 45 F to 65 F.

The shaded portion of Figure II-4 is the effective temperature range most desired when scheduling construction activities. A low temperature of 15 F and a high temperature of 105 F are extreme points beyond which human productivity falls to a level that is uneconomical to proceed with construction. At these temperature extremes, human efficiency has been reduced to a level of approximately 40 percent. This is a level which all construction superintendents in the study agreed to as a lower most limit of acceptable

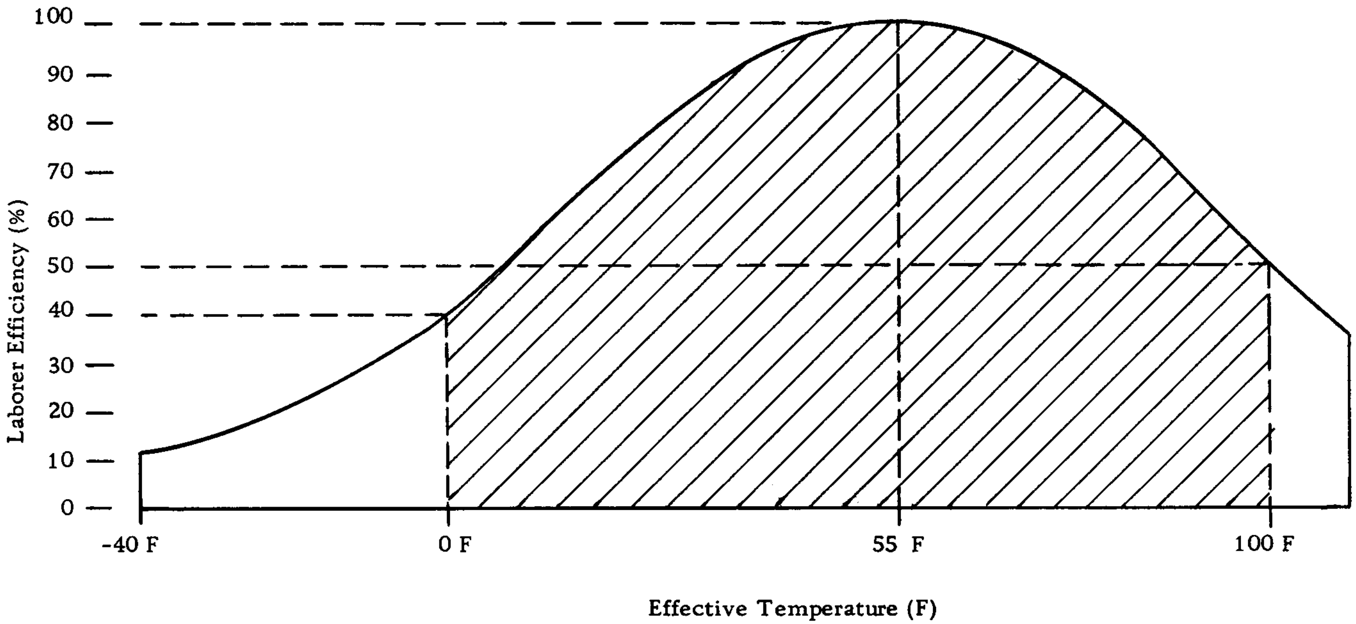


Figure II-4. Effective temperature vs laborer efficiency.

efficiency.

Figure II-4 relates human efficiency as a function of effective temperature. It is possible to add a third dimension, air velocity, to Figure II-4. At the temperatures near the middle of the temperature range in Figure II-4, a slight breeze up to approximately 10 mph slightly increases the efficiency of laborers. Towards the extreme ends of the effective temperature range, even a slight breeze is undesirable. When the air velocity increases to 35 mph or greater, construction work may be stopped as a safety precaution. The effects of wind on laborer efficiency are illustrated in Figures II-5 and II-6, for 15 F and 55 F. Figures II-5 and II-6 were derived from observations of laborers under actual working conditions in Montana and Oregon.

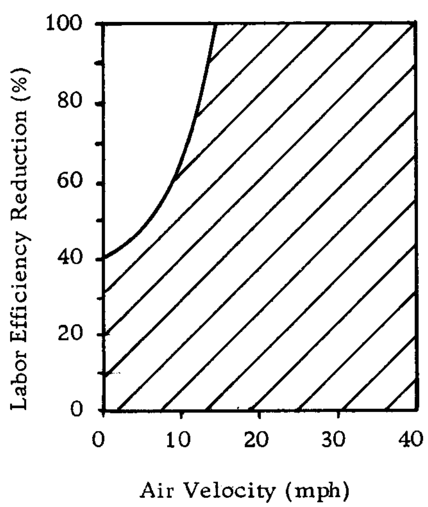


Figure II-5. Air velocity and percent labor efficiency reduction at 15 F.

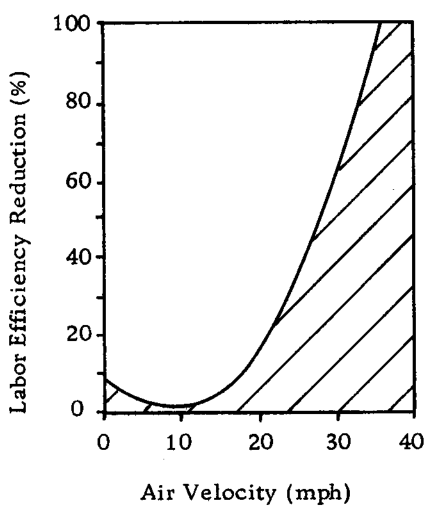


Figure II-6. Air velocity and percent labor efficiency reduction at 55 F.

Figures II-4, II-5, and II-6 can be combined to form a three-dimensional model which shows human efficiency as a function of temperature, humidity, and air velocity. This is shown in Figure II-7.

The information presented in Figure II-7 must be carefully considered before using it in analysing the construction schedule. It may be desirable to alter the efficiency ratings to satisfy the requirements for specific activities since the model shows only the average effects for construction activities in general.

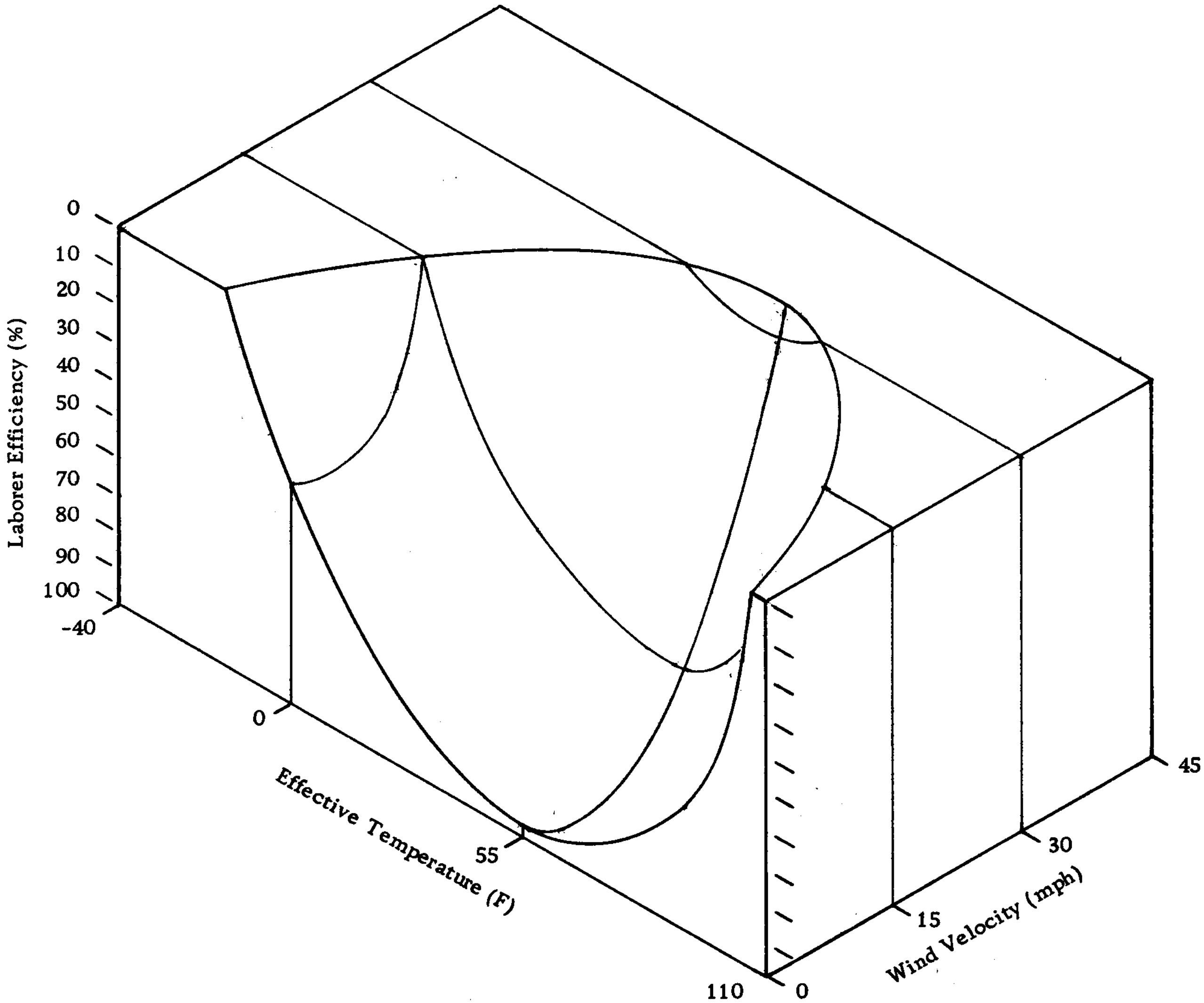


Figure II-7. Laborer efficiency vs effective temperature and air velocity.

III. EQUIPMENT DELAYS

> Job efficiency is the most complex element of production estimating (5, p. 71).

When estimating equipment delays; two general concepts must be considered. The first is that of job delays, the second is job efficiency. Job delays are those factors which require the operator or operators to stop the unit of equipment in operation. Job efficiency, however, has a broader meaning. It not only includes job delays, but also those factors which interact to produce conditions that are less than ideal for the operation of any particular unit of equipment.

Job Delays and Job Efficiency

To illustrate the importance of job delays and job efficiency, statistical compilations have been made by the Highway Research Board of the National Research Council for specific types of heavy earth moving equipment.

Studies on the performance of rubber tired tractor scrapers by the Highway Research Board of the National Research Council (5, p. 68), indicate weather (rain, cold, and wet grades) as the greatest cause of job delays. This may represent as much as 50 percent of the total available working time. Other delays, such as the time required to open up cuts, trim slopes, maintain and repair equipment, and time lost from lack of operators, are relatively small by comparison. Since delays due to weather generally involve shutdowns of 15 minutes or more, they are considered major delays. Delays of 15 minutes or less in duration are referred to as minor delays.

Without further elaboration, it is obvious that delays in equipment operations are luxuries and run into costs which reduce job profits.

Equipment Delay Report

A simple and efficient method for obtaining information about equipment delays is the Equipment Delay Report form in Figure III-1. This report form is designed to be placed on a clipboard and attached to the unit of equipment being studied. All equipment operators are required to fill in this form for all delays to the nearest minute of down-time according to the operator's own watch, thus requiring no special equipment. Maintaining this form is simple and will not interfere with the operator's duties since he is called upon to make the few notes required on the form only after a shut-down has been initiated and idle time is thus available to the operator.

The equipment delay reports can then be tabulated for each work shift. When the daily reports have been tabulated for a week or more of operation, patterns in the delays may begin to appear.

EQUIPMENT DELAY REPORT

John Doe Contractors
Date ______________________
Equipment Unit No. ______________________

Corvallis, Oregon
Project ______________________
Operator ______________________

Delay No.	Elapsed Time		Delay (min.)		Cause of Delay
	Stop	Start	Minor	Major	
1	-	8:18		:18	Servicing
2	8:32	8:35	:03		Wait for pusher
3	9:16	9:23	:07		Water - engine
4	10:14	11:22		1:08	Wait for pusher
5	1:18	2:52		1:34	Snow shower
6	3:12	3:16	:04		Repair engine
7	4:06	5:00		:54	Wait for pusher
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
Total Time			14	3:54	
% of Total Time					

Figure III-1. Equipment Delay Report form.

Finally, monthly reports may be prepared with the total time for each type of delay. Some of the delays which may occur are shown in Figure III-1.

The Equipment Delay Report may be adapted to any length of work shift, although a work shift is usually considered an eight-hour interval. Each delay is recorded with the stoppage of the unit of equipment signifying the start of a delay and the return to use of the unit of equipment signifying the end of the delay. The delay is recorded as major if it is 15 minutes or greater in duration and minor if 15 minutes or less in duration. A description of the delay and its cause are recorded in the last column of the Equipment Delay Chart. If the delay is due to precipitation, an estimate as to the amount and type of precipitation should be included. It may be possible to verify the exact conditions for the delays at a later date. If not, the operator's personal evaluation will have to suffice.

To complete the Equipment Delay Report, the total time lost to major and minor delays are recorded and the length of the work shift at the end of the shift. The percent of the total time is then computed for the major and minor delays and the total amount of time the unit of equipment was actually in use.

As data are collected for each unit of equipment, a familiarity with the unit of equipment is developed to the extent that, with the knowledge of the probabilities of occurrence of the factors causing the equipment delays, the job efficiency to be expected from that particular unit of equipment may be closely approximated.

IV. STOCHASTIC WEATHER PROCESSES

> Climatological predictions given by per cent chance are the best estimate of what the weather will be several months or years from now, but the synoptic forecast gains in reliability as the time (day, week, or month) in question comes closer (13, p. 3).

If it were possible to predict weather accurately, construction activities could be scheduled to take advantage of the more favorable weather conditions, while alternate schedules could be considered to avoid unnecessary project shut-down during periods of adverse conditions (3, p. 3).

Despite the claims of some private forecasters, the current state of knowledge of the properties and phenomena of the atmosphere do not permit a reliable long range weather forecast. Climatological predictions based on the probability of occurrence of various weather phenomena that have occurred present the best estimate of the weather conditions several months or years from now.

Unlike the climatological forecast, the synoptic, or short range, forecast gains in reliability as the time in question draws nearer. The climatological forecast can aid in scheduling activities by giving the probability of weather conditions for the period in question, but the final decision for work to continue must be based on the synoptic forecast.

Climatological Data

Large volumes of climatological data have two basic characteristics: 1) the individual phenomena display considerable variability, but 2) the total sum of these items displays stability and reliability (18, p. 6). To visualize these characteristics in a sample of data, the occurrences of specific phenomena may be grouped according to their magnitude. Figure IV-1 is the frequency distribution for daily maximum temperatures during the month of June in Portland, Oregon. From the distribution in Figure IV-1, the probability of the temperature being any specific value can easily be determined.

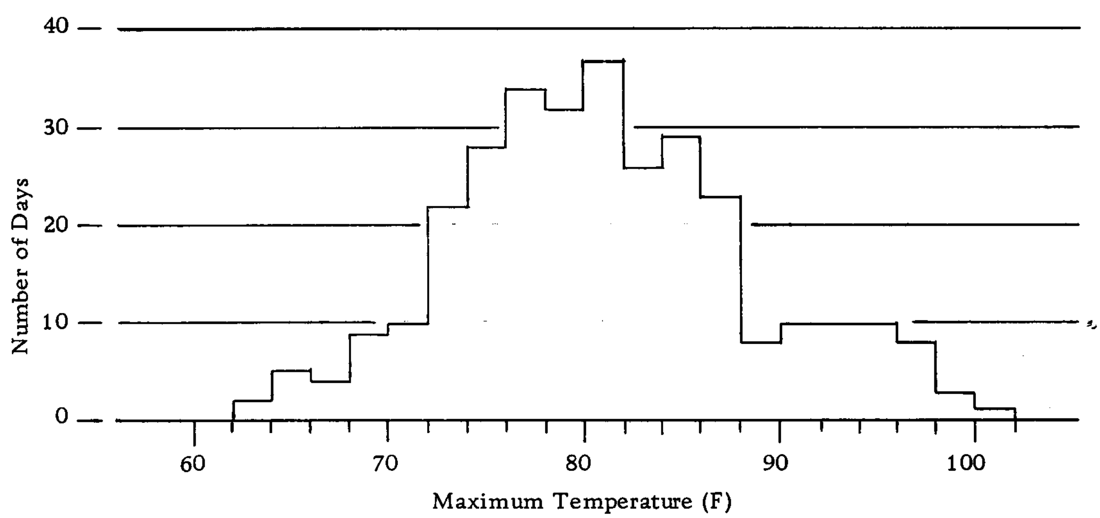


Figure IV-1. Frequency distribution of maximum daily temperatures during June in Portland, Oregon (18, p. 6).

The probability of a certain event is the degree of assurance of its occurrence. The probability of an event is determined by dividing the number of occurrences of the event by the number of times it could have occurred. For example, if in a period of ten years a weather station recorded precipitation on 42 days in June, then the estimated probability of a rainy day in June at the station is 42/ 300. This fraction equals 0.140, or the probability is 14 percent. The probability of a NON-rainy day in June at the station is (1 - 0.140), or 86.0 percent.

Suppose that two events may or may not occur simultaneously. Assume that the occurrence of one event has no influence on whether the other event occurs. The two events are then said to be independent. To estimate the probability that both events will occur simultaneously, consider the following example. The probability of a day in June being a Thursday is 1/7. Assuming that a day in June having rain and a day in June being a Thursday are independent, then the probability of a day in June being a rainy Thursday is estimated by finding the product of the simple probabilities: (42/ 300) x (1/7), or 0.020. Since half the Thursdays in June, over a period of years, are odd-numbered, the probability of an odd-numbered rainy Thursday in June is (42/ 300) x (1/7) x (1/2), which is 0.010, or one percent.

If we assume that the same weather station has observed 121 days with a maximum temperature in the 60's during the same period, and that the maximum temperature and precipitation are independent, then the probability of a rainy day in June with the maximum temperature in the 60's is (42/300) x (121/300), or 5.6 percent. Like most weather phenomena, the two conditions are not independent. Instead, it may be that there were 34 rainy days during the study period with maximum temperatures in the 60's out of a total of 42 rainy days. The probabilities would then be:

The probability of a rainy day in June is 42/300 . . . 14.0%

The probability of a day with a maximum temperature in the 60's is 121/300 . . . . 40.3%

The probability of a rainy day in June with the maximum temperature in the 60's is 34/300 . . . . 11.3%

The probability of a day with a maximum temperature in the 60's <u>relative</u> to the occurrence of rain is 34/42 . . . . 81.0%

The probability of a rainy day <u>relative</u> to a maximum temperature in the 60's is 34/121 . . . . 28.1%

The last three probabilities are much greater than the 5.6 percent computed when a rainy day in June and a maximum temperature in the 60's were considered as separate events.

Climatological records can be obtained from the U. S. Department of Commerce, Weather Bureau for a nominal fee. Summaries of the hourly weather conditions plus the weekly and monthly totals make them a very useful tool in statistical studies. Other governmental and private agencies also publish summaries of weather phenomena for specific localities. Tables of the frequencies of daily precipitation amounts and the extremes in daily temperatures for Portland are reproduced in Tables IV-1, IV-2, IV-3, and IV-4. These were compiled and made available to the public by William P. Lowery, Research Meteorologist, for the Oregon Forest Lands Research Center at Corvallis, Oregon. The figures tabulated are based on the actual observations made at Portland, Oregon, during the years 1948-1958, and are presented on the basis of "days per 100 days."

Contingency Tables

From sample Equipment Delay Reports[1] that were filled out during interviews conducted on construction projects, Table IV-1 lists some of the more frequently encountered activities and the effects of various weather conditions upon the construction efficiency. The factors in Table IV-5 were determined by comparing the actual construction duration with the activity duration that could be expected under ideal working conditions. Although this presents us with a

[1] Interviews with construction firms in Montana and Oregon were conducted to determine some of the effects of weather on human and equipment performance. Reports of the form in Figure III-1 were completed and returned for analysis. The most significant reports were returned by Mr. Vance Rogers, job superintendent for the Lowe Construction Company of Billings, Montana. The effects of cold temperatures and of various types of precipitation (rain, snow, etc.) on the performance of humans and mechanical equipment were fully described and recorded. Additional reports completed by other construction firms in Montana and Oregon substantiated Mr. Roger's reports.

Table IV-1. Frequency of daily minimum temperatures at Portland, Oregon, as days in 100 days.

Period		Temperature, degrees F							
		Below 0	0-9	10-19	20-29	30-39	40-49	50-59	60-69
	1 - 10			4	21	57	18		
Jan.	11 - 20		3	8	25	43	19	2	
	21 - 31	1	3	16	17	41	22		
	1 - 10	1	2	3	24	45	24	1	
Feb.	11 - 20			2	13	60	25		
	21 - 29				11	64	24	1	
	1 - 10			1	15	59	24	1	
Mar.	11 - 20				11	59	30		
	21 - 31				2	51	47		
	1 - 10				1	54	45		
Apr.	11 - 20					29	66	5	
	21 - 30				1	42	51	6	
	1 - 10				1	13	63	23	
May	11 - 20					6	63	31	
	21 - 31					5	56	38	1
	1 - 10						39	56	5
June	11 - 20						30	66	4
	21 - 30						21	74	5
	1 - 10						17	78	5
July	11 - 20						3	82	15
	21 - 31						6	84	10
	1 - 10						5	85	10
Aug.	11 - 20						6	79	15
	21 - 31						16	70	14
	1 - 10						31	64	5
Sept.	11 - 20					2	37	61	
	21 - 30					7	51	41	1
	1 - 10					8	60	32	
Oct.	11 - 20				2	16	59	23	
	21 - 31					41	52	7	
	1 - 10				4	44	47	5	
Nov.	11 - 20			3	9	38	45	5	
	21 - 30			1	21	34	40	4	
	1 - 10				13	53	33	1	
Dec.	11 - 20				15	50	35		
	21 - 31				16	59	23	2	

Table IV-2. Frequency of daily maximum temperatures at Portland, Oregon, as days in 100 days.

Period		Temperature, degrees F									
		10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	99+
	1 - 10		3	20	61	16					
Jan.	11 - 20		7	22	49	20	2				
	21 - 31	1	12	26	40	20	1				
	1 - 10	1	4	14	44	36	1				
Feb.	11 - 20			10	47	39	4				
	21 - 29			2	45	42	11				
	1 - 10			5	40	49	5	1			
Mar.	11 - 20				36	55	8	1			
	21 - 31			1	11	70	17	1			
	1 - 10				5	55	26	14			
Apr.	11 - 20				4	43	33	17	3		
	21 - 30				5	45	35	13	2		
	1 - 10					26	51	16	7		
May	11 - 20					19	40	24	17		
	21 - 31					15	45	29	11		
	1 - 10					8	38	41	8	5	
June	11 - 20					5	43	39	11	2	
	21 - 30						49	35	11	5	
	1 - 10						21	45	27	7	
July	11 - 20						6	52	34	7	1
	21 - 31						12	46	37	4	1
	1 - 10					1	10	57	25	7	
Aug.	11 - 20						7	52	29	12	
	21 - 31						20	53	22	5	
	1 - 10						18	39	35	8	
Sept.	11 - 20					1	29	47	19	4	
	21 - 30					4	44	35	12	5	
	1 - 10					20	54	19	7		
Oct.	11 - 20					31	53	16			
	21 - 31					7	51	39	3		
	1 - 10					7	73	20			
Nov.	11 - 20			5	2	34	54	5			
	21 - 30				4	39	51	6			
	1 - 10			1	8	54	37				
Dec.	11 - 20				10	56	33	1			
	21 - 31				18	55	25	2			

Table IV-3. Precipitation and restrictions to visibility at Portland . . . . frequencies in days/100 days.

		Fog	Thunder	Sleet	Hail	Rain	Snow	Glaze	Dust storm	Smoke, haze	Blowing snow
	1 - 10	38		2		74	26	3		30	2
January	11 - 20	41		8	2	68	32	5		30	3
	21 - 31	46		4	2	64	30	7		40	2
	1 - 10	42	1	3	1	70	17	8		33	
February	11 - 20	41		1	1	75	19	1		32	
	21 - 29	40		2	7	71	11	2		43	
	1 - 10	43			1	65	25			37	
March	11 - 20	30	2		7	74	8			30	
	21 - 31	28	2		1	73	3			28	
	1 - 10	21	3		4	63	3			33	
April	11 - 20	23	3			52	1			25	
	21 - 30	20	4		1	63	2			22	
	1 - 10	26	6		6	58	1			25	
May	11 - 20	16	3		1	54				20	
	21 - 31	10	7		1	48				11	
	1 - 10	12	7			50				16	
June	11 - 20	20	6			53				15	
	21 - 30	11	1			43				12	
	1 - 10	8	3			26				10	
July	11 - 20	5	3			20				12	
	21 - 31	8				18				13	
	1 - 10	9	3			21				24	
August	11 - 20	16				20				34	
	21 - 31	22	3			34				41	
	1 - 10	25	3		1	26				45	
September	11 - 20	52	3		1	35				60	
	21 - 30	57	2			45				66	
	1 - 10	53	3		2	57				54	
October	11 - 20	63	2			53				69	
	21 - 31	72	1		2	59	1			61	
	1 - 10	67			1	54				60	
November	11 - 20	59	1	1	2	70	7	2		36	
	21 - 30	60	2			64		1		47	
	1 - 10	45			3	79	12	2		29	
December	11 - 20	45		3		75	13	4		31	
	21 - 31	45	1	3	2	77	19	3		27	

Table IV-4. Daily precipitation amounts at Portland, Oregon .... frequencies in days per 100 days.

		None	Trace .01-.09 in.	.10-.19 in.	.20-.29 in.	.30-.39 in.	.40-.49 in.	.50-.59 in.	.60-.69 in.	.70-.79 in.	.80-.89 in.	.90-.99 in.	>.99 in.	Daily mean in.
January	1 - 10	23	34	11	7	5	6	3	2		1	1	8	.25
	11 - 20	22	29	11	10	11	1	3	4	2	3	1	5	.23
	21 - 31	24	37	11	10	5	3	2	3	1	1	1	3	.17
February	1 - 10	26	38	9	10	4	3	1	3	2	2	1	2	.16
	11 - 20	22	36	12	9	3	4	1	7	2	1	1	3	.19
	21 - 29	27	37	13	3	2	2	4	3	2	1		3	.16
March	1 - 10	32	33	12	4	8	5	1			3	1	1	.13
	11 - 20	25	39	10	12	5	4	3	1	2				.12
	21 - 31	27	34	18	7	3	3	2	2		1		1	.13
April	1 - 10	37	35	14	6	3	2	2	1					.08
	11 - 20	48	28	9	5	6	2	1		1			1	.08
	21 - 30	37	38	14	5	3	1	2	1					.07
May	1 - 10	42	35	7	5	4	2	2	1				2	.09
	11 - 20	46	38	7	5	2	1		1					.04
	21 - 31	52	30	8	3	2	2	1	1			1		.06
June	1 - 10	49	33	6	2	3	1	3	1	1			1	.08
	11 - 20	47	36	8	5	2	2	2						.06
	21 - 30	57	28	6	2	4			1	1	1			.05
July	1 - 10	74	21	3	3									.01
	11 - 20	80	17	1		1					1			.01
	21 - 31	81	15	2	1			1						.01
August	1 - 10	78	14	3	2	2		1						.02
	11 - 20	79	15	1	3							1		.02
	21 - 31	66	24	3	2	1	1	1	2				1	.05
September	1 - 10	73	18	3	3	2				1·				.03
	11 - 20	65	25	5	2		2	2						.03
	21 - 30	56	24	4	4	5	1	2	1	3			2	.10
October	1 - 10	43	23	7	5	6	4	1	2	3	3		3	.17
	11 - 20	47	30	9	3	2	3	3		2		1		.09
	21 - 31	41	22	14	9	3	2	2	1	2	1	1	3	.15
November	1 - 10	46	25	12	5	4	4	1	1	1	1			.09
	11 - 20	25	27	15	11		7	5	2	2	1	1	4	.22
	21 - 30	36	23	6	9	8	4	3	4		2	4	1	.20
December	1 - 10	19	25	10	13	6	7	5	4	6	1	1	3	.25
	11 - 20	24	21	7	12	9	2	2	2	1	1	1	3	.18
	21 - 31	18	39	7	13	5	7	5	3	1	1		2	.19

Table IV-5. Activity performance expected for some construction activities under various conditions of temperature and precipitation.

No.	Activity Description	Activity Efficiency, % Optimal Performance		
		Precipitation		Temperature
		0.00-0.50	Greater than 0.50	10 F - 32 F
1	Preliminary sitework	100	60-75	80-90
2	Excavating and backfilling	90-100	25-50	0-50
3	Concrete breaking, wrecking, drilling, etc.	100	75-90	70-100
4	Scaffolding and hoisting towers	100	50-75	80-90
5	Concrete footings, foundations, and retaining walls			
	form	100	70-80	80-90
	pour	100	25-50	0
6	Reinforced and architectural concrete			
	form	100	70-80	80-90
	pour	100	25-50	0
7	Concrete floors and walks, curb and gutters, and concrete masonry	90-100	0	0
8	Brick masonry, glass block, stonework, roof tile, etc.	90-100	0-90	0
9	Rough carpentry	90-100	70-90	60-90
10	Painting (exterior)	0-100	0	0
11	Roofing, corrugated asbestos and metal roofing and siding	100	50-75	60-80
12	Sheet metal work	100	0-25	70-90
13	Steel and aluminum windows and storefronts	100	0-100	90-100
14	Structural and miscellaneous iron and steel construction	100	10-50	70-90
15	Plumbing	100	40-80	70-90
16	Electrical	100	85-95	90-95
17	Asphalt paving	100	0	0

table of values that are easy to comprehend, the problem of determining the amount of delay due to each weather condition, such as precipitation, temperature, or wind, is not readily apparent.

It is not easy to isolate the effects of each weather condition on the equipment and men used to complete a specific activity. If each weather condition affects the job efficiency independently of the other weather conditions, then it would be a relatively simple task to compute the expected activity durations from past weather data. However, the use of machines and men makes it necessary to determine if the effects of weather on one is independent from the effects of weather on the other.

Statisticians have developed three powerful techniques for the study of relationships between various factors. These are contingency tables, analysis of variance, and regression analysis. Contingency tables reveal associations between classifications. The analysis of variance reveals, and to a certain extent measures, the relationship between a given (preferably a normally distributed) variable and one or more classifications. It also analyses the total variance of the variable into its component parts. Regression analysis reveals the measure's functional relationships between two or more variables. Only the first of these techniques, contingency tables, will be considered here. The rest are left to the reader if other methods of analysis are desired.

Table IV-6 illustrates the simplest form of a contingency table (10, p. 503). It is a two-way classification table with respect to the activity efficiency of precipitation on preliminary sitework.

Table IV-6. Effect of precipitation on preliminary sitework.

Precipitation	Time Attributed to Major Delays (Min.)	Productive Time (Min.)	Total
0.00 - 0.50	0	480	480
0.50 & greater	192	288	480
TOTAL	192	768	960

The horizontal classification divides the activity time into two classes according to the time lost to major delays and the total productive time, that is, when equipment and men are working. The vertical classification divides the weather into two classifications according to the amount of precipitation. The contingency table itself cross-classifies the activity efficiency with respect to these two bases of classification.

The problem the contingency table seeks to solve is whether one classification is independent of the other. For example, Table IV-6 aids in giving an answer to the question: Does the amount of precipitation have any effect on the length of activity duration? The test associated with the contingency table is thus one of independence.

When an item is cross classified, as in Table IV-6, if the frequencies of each row are proportional to those of all other rows, or if the frequencies of each column are proportional to those of all other columns, then the two classifications are independent of each other. If a universe of items, however, shows the proportionality of frequencies characteristic of independence, a random sample from that universe will very likely not have the same properties, as a result of the uncertainties of sampling. A cross-classification of sample data that does not have exactly proportional frequencies is therefore not a proof that the universe frequencies are not proportional and the classifications therefore dependent. The question that has to be answered by the analysis is: By how much must a contingency table of sample data depart from the proportional pattern before it is reasonable to conclude that in the universe as a whole the classifications are dependent?

The statistical device that is used to test the hypothesis of independence is the χ^2 test (10, p. 504). Frequencies are obtained for each cell of a contingency table that would be expected for that cell if the hypothesis of independence were true and if the universe proportion for each marginal classification were the same as the sample proportions. These theoretical or expected frequencies are then compared with the actual sample frequencies by means of the χ^2 test.

The process may be illustrated by reference to Table IV-7. This shows the cross-classification of 960 minutes of work time with respect to the total amount of precipitation that fell during that time. The frequencies are not in proportion; but the question is: Do they deviate sufficiently from proportional frequencies to justify the conclusion that the variation in precipitation affects the activity efficiency, or can the deviation from proportionality be reasonably attributed to sampling? To compute the frequency expected for each cell on the hypothesis of independence, we take the total for each column and redistribute that total among the various rows in the same proportions as the grand total is distributed in the row total column. We then get a set of cell frequencies that are proportional in the same way that the row or column totals are proportional. In Table IV-7, the row totals are in a 1 to 1 ratio (480:480). Therefore, the cell frequencies in the first row that we would expect on the assumption of independence should have a 1 to 1 ratio with the cell frequencies of the second row, column by column, are

$$\frac{96}{96} = \frac{384}{384} = \frac{480}{480}.$$

Table IV-7. Effect of precipitation on preliminary sitework.

Precipitation	Time Attributed to Major Delays (Min.)	Productive Time (Min.)	Total
0.00 - 0.50	0 (96)	480 (384)	480
0.50 & greater	192 (96)	288 (384)	480
TOTAL	192	768	960

If we wish, we can work the other way. The ratio of the column totals is $\frac{96}{384} = 0.240$. Therefore, the cell frequencies in the first column that we would expect on the assumption of independence should be 0.240 times the cell frequencies in the second column, row by row. Thus, in Table IV-7, we have

$$\frac{96}{384} = \frac{96}{384} = \frac{192}{768}.$$

It should be emphasized that the theoretical frequencies obtained in this way are those that would be expected on the assumption of independence, together with the assumption that the ratios of the row and column totals in the universe are the same as those in the given sample.

To test the hypothesis of independence for Table IV-7, we compute

$$\sum \frac{(F_i - f_i)^2}{f_i} = \frac{(0-96)^2}{96} + \frac{(182-96)^2}{96} + \frac{(480-384)^2}{384} + \frac{(288-384)^2}{384} = 240.0$$

and compare this result with the $\chi^2_{0.05}$ point for the proper value of n, assuming that we have set the risk of rejecting the hypotheis when it is true at 0.05.

The n of a χ^2 test is associated with the "degrees of freedom" involved in the testing procedure.

In a test of independence, the number of degrees of freedom are determined by counting the number of independent restrictions placed upon the theoretical frequencies when they are being determined and subtracting this number from the number of comparisons made between theoretical and actual frequencies. In our case we required that the expected cell frequencies add by rows to 480 and 480, respectively, and by columns to 192 and 768 respectively. The imposed restrictions are then:

$f_{11} + f_{12}$ = total for row 1

$f_{21} + f_{22}$ = total for row 2

$f_{11} + f_{21}$ = total for column 1

$f_{12} + f_{22}$ = total for column 2

Since any one of these can be obtained from the other three, only three of the restrictions are independent. Altogether, theoretical frequencies were determined for four cells. Since they were subjected to three independent restrictions, the degrees of freedom (n) are 4 - 3 = 1.

Therefore for a two by two contingency table, the critical value of χ^2 (assuming a = 0.05) is the $\chi_{0.05}^2$ point for one degree of freedom, 3.84 (20, p. 451). In our sample, this is much less than the sample result (240.0). We therefore reject the hypothesis of independence and conclude that the variations in precipitation do have some effect on the activity duration.

Although this conclusion is one which we were certain of even before using the contingency table test on the data, it is not the particular example used but the method of testing for dependency or independency that is of value. Extending the contingency table to an r x s table, we can test the effects of different categories of major or minor delays on an activity for independency. The extension of the contingency table to a r x s table is described in detail by A. M. Mood and F. A. Graybill in "Introduction to the Theory of Statistics" (20, p. 313).

Probability Calendars

After the equipment and labor elements of the activities have been tested for independence or dependence on various weather phenomena, it is desirable to produce a chart relating the frequencies of specific weather conditions to their effects on performance. One method is to plot the expected productivity as a function of the probability of occurrence of that particular level of productivity. This is shown on the "probability calendar," Figure IV-2, redating the expected efficiency levels for manual labor outdoors during a one year period.

Figure IV-2 was derived by correlating the frequencies of maximum daily temperatures from Table IV-1, page 38, and the effects of temperatures on human production, Figure II-3. The abcissa of the probability calendar is expressed in 10-day increments. This facilitates the derivation of the probability calendar by requiring the plotting of fewer points. Any smaller intervals of time are not necessary since the statistical change in weather conditions over a period of many years show only slight day-to-day variations.

In Figure IV-2 efficiency values of 60 percent, 75 percent, 90 percent and 100 percent for human efforts were selected, with 100 percent representing the optimal productivity that could be expected under ideal conditions.

Several aspects of Figure IV-2 are worth noting. Human performance is generally at its peak during the periods from December 1 to May 1 as a function of the frequency of maximum daily temperatures. This is where the maximum daily temperatures are generally in the 50 F to 60 F range, the range of optimal temperatures for human performance. During the periods from July 1 to September 15, human performance drops to about 80 percent of the optimal value.

Another form of the probability calendar is shown in Figure IV-3. This is for the pouring of concrete slabs. The experience of contractors indicates that if there is greater than 0.10 inches of precipitation during a 24-hour period, there is a relatively high probability that a concrete slab could not be properly finished unless the work area was sheltered from natural weather phenomena. In Figure IV-3 the probability of being able to pour a concrete slab has only two factors to consider: either a pour can be made or it cannot be made. The line on Figure IV-3 indicates the probability of a successful pour.

It is interesting to compare Figures IV-2 and IV-3. When human productivity is at its optimal level from December 1 to May 1, the probability of experiencing a successful concrete pour is at its lowest level. When the probability of a successful concrete is at its highest level during the summer months, the productivity of the laborers is at a decreased level.

Since delays in activity duration are most commonly measured in dollars and cents, how can this information be used to determine more reliable time estimates where weather may delay construction?

Figure IV-2a. Probability calendar for 100% and 75% efficiency levels of human laborers in Portland, Oregon.

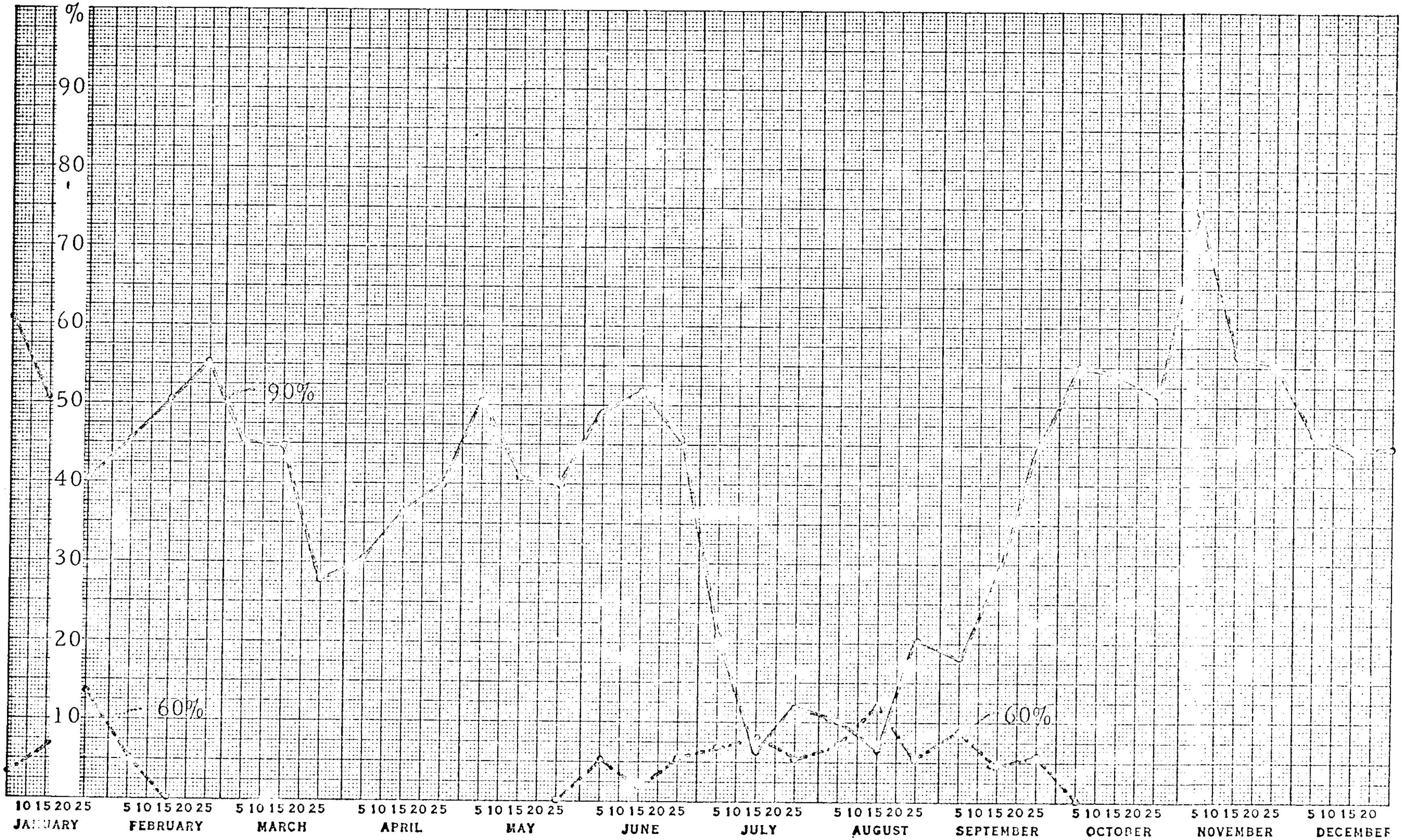


Figure IV-2b. Probability calendar for 90% and 60% efficiency levels of human laborers in Portland, Oregon.

Figure IV-3. Probability calendar for successful pouring of concrete slabs in Portland, Oregon.

One possible method for considering these variables as part of a critical path analysis is discussed in the next chapter.

V. CRITICAL PATH ANALYSIS

Simulation models of operating systems have been growing rapidly and are tending to become a dominant technique in assisting in decision making processes as well as for comparing basic alternatives for operating policy. Through the use of simulation models, it is possible to determine the effects of many alternative policies without tampering with the physical system. Simulation reduces the risk of upsetting the real system without the prior assurance that the contemplated change will be beneficial (8, p. 505).

Historic data may be used to simulate working conditions which may be anticipated during the construction period. More reliable time estimates may then be derived for activity durations. A procedure based upon historic data should, then, be capable of providing a most likely time estimate tailored to the conditions anticipated during the construction period. Such a procedure has merit if the following conditions are satisfied (19, p. 227).

> The historical data are representative of those conditions expected to prevail in the future when the activity in question is to be performed.
>
> The sample of historical data must be of sufficient size to assure that the effects observed are representative of the effects which may be anticipated in the future.

Thus far we have studied methods of collecting and analysing data to determine the effects of weather on human and equipment performance, Chapters II, III, and IV. In Chapter IV, weather conditions were analysed using contingency tables to determine if they were independent of activity durations. The data were then correlated and used to produce a chart in the form of "efficiency probability calendars," Chapter IV. To illustrate this form of chart, the probability efficiency calendars for manual human performance and the probability of successfully pouring a concrete slab were derived, Figures IV-2 and IV-3.

The first form of probability calendar is applicable only to manual tasks such as hammering, whereas the latter carries the additional assumption that the efficiency ratings include the affects on human performance.

Strikes and other factors which cause delays in construction duration may be similarly analysed. Thus, a construction project could be simulated prior to the initiation of construction. It would then be possible to consider the effects of alternate starting dates, alternate building techniques, and to aid in the determination of future manpower requirements necessary to successfully complete the project on schedule.

Average Probability Calendars

The probability calendars in Figures IV-2 and IV-3 do not present the performance characteristics that are easiest to work with in a CPS analysis. What is desired is the average level of performance that may be anticipated during the time intervals on the probability calendar. It is also desirable to indicate the optimistic performance level which is bettered only one time in ten, and the pessimistic performance level which is exceeded only one time in ten. They are indicated, respectively, as $a_{.10}$ and $b_{.90}$. This becomes useful when the effects of being overly optimistic or pessimistic are required from the critical path analysis.

Moder and Phillips (19, p. 226) have presented two notable reasons for the use of $a_{.10}$ and $b_{.90}$ in PERT analysis. First, it is not realistic to ask for estimates of a and b based on the user's experience. The values a and b in PERT analysis are defined as the ultimate limits of the hypothetical distribution of performance times and, hence, they cannot theoretically ever have been experienced. The second reason is purely on statistical grounds. It can be shown that the range, $b_{.90} - a_{.10}$, varies over a narrow range of 2.5 to 2.9 standard deviations for a wide class of distributions (rectangular, exponential, triangular, normal, and beta) and for any location of the mode of the distribution. This is not true for the range b - a, which deviates from six standard deviations quite markedly as we change the shape of the distribution. It varies all the way from 3.4 standard deviations for the rectangular distribution, to the assumed value of 6 for the beta distribution, and to plus

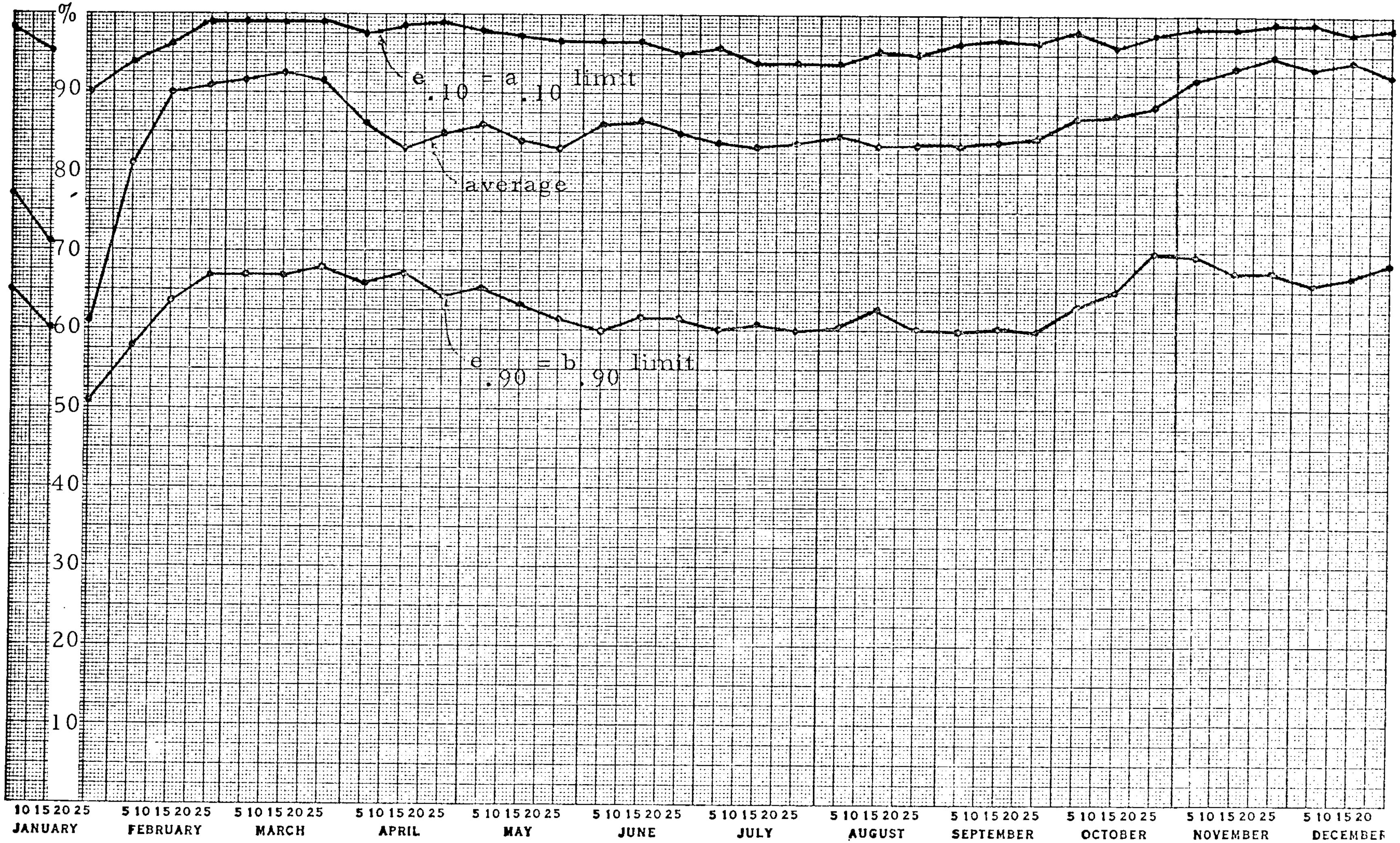


Figure V-1. Average probability calendar for the performance level of human laborers, Portland, Oregon.

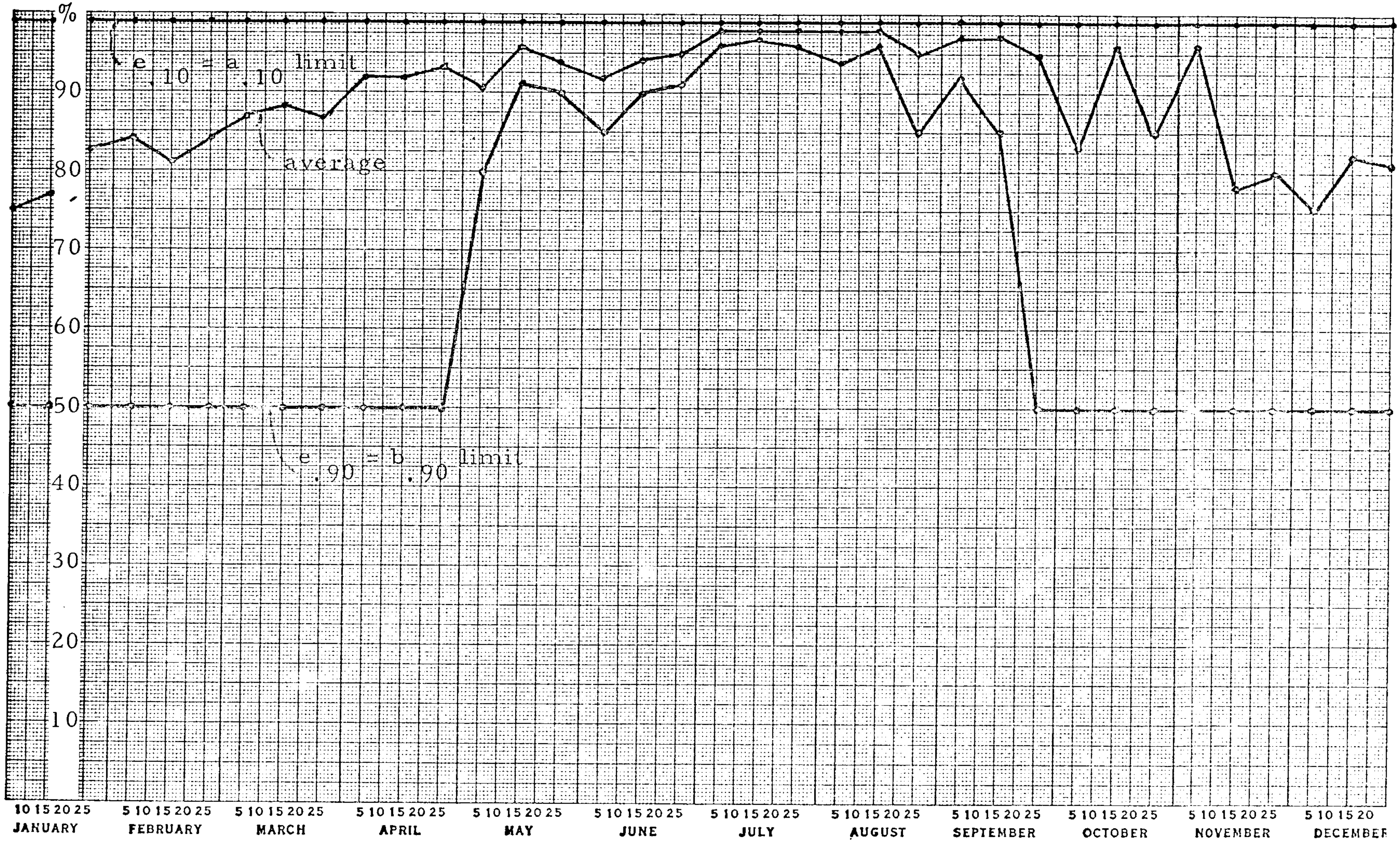


Figure V-2. Average probability calendar for the performance of mechanical equipment, Portland, Oregon.

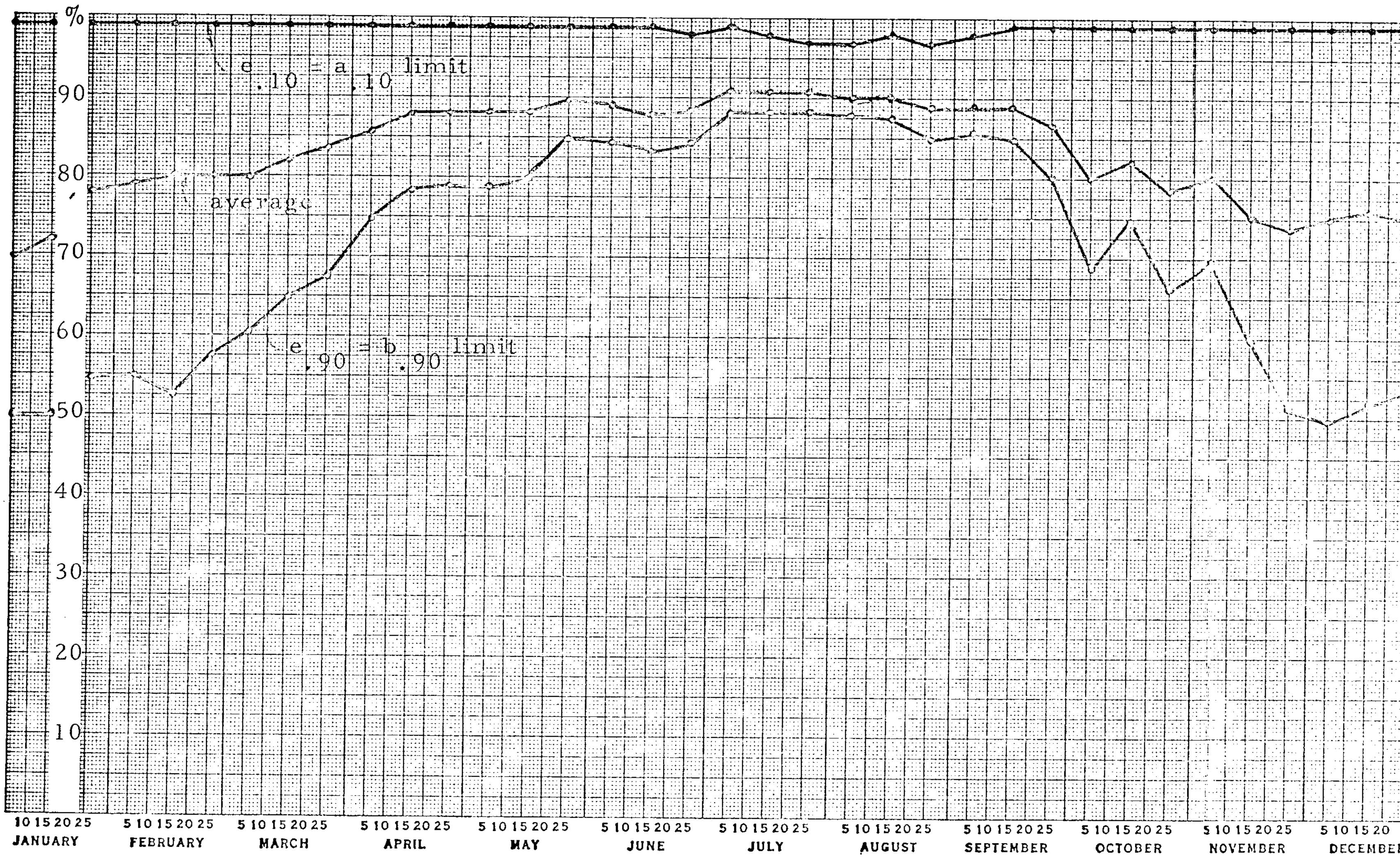


Figure V-3. Average probability calendar for the successful pour of concrete slabs in Portland, Oregon.

infinity for the normal distribution. Since the shape of the distribution of performance times is generally not known, the use of these limits present quite an advantage to estimating activity times.

The new estimates for a and b may then be used in the following equation where t_e is the expected time.

$$t_e = (a_{.10} + 4m + b_{.90})/6 \qquad \text{(eq. V-1)}$$

The value of m is the normal expected time for the activity duration. Since the expected time represents the distribution of the activity durations, the estimate may be said to be an aposteriori estimate. This is in contrast to the estimated activity time derived by using historic data which would then be an apriori estimate since the activity itself does not have to be subjected to many observations, but only the effects on the components of the activity, which may be repeated in many other activities, are analysed to evaluate an expected time for the activity duration.

Figures V-1, V-2, and V-3 illustrate the revised form of the probability calendars in Figures IV-2 and IV-3 showing the average performance level anticipated during a ten-day interval of time, along with the $a_{.10}$ and $b_{.90}$ limits for the same period of time.

Performance Nomographs

If the relationships between three variables, u, v, t, can be expressed in the form (4, p. 2-85)

$$f_1(u) + f_2(v) = f_3(t), \qquad \text{(eq. V-2)}$$

then they can be represented graphically by a very convenient form of diagram called a nomograph. In its simplest form there are three scales (straight or curved), along which the values of the three variables are marked in such a way that any three values of t, u, v, which satisfy the given equation are represented by three points which lie in a line. Hence, if the values of any two of the variables are given, the corresponding value of the third can be found by simply drawing a straight line through the two given points and reading the value of the point where it intersects the third scale.

If in equation V-2, $f_1(u)$ is a function of u alone, $f_2(v)$ is a function of v alone, and $f_3(t)$ is a function of t alone, then a nomograph can be constructed as follows:

> Choice of Moduli to Fit Size of Paper (4, p. 2-85). Let $f_1(u')$ be the smallest and $f_1(u'')$ the largest value of $f_1(u)$ likely to be needed, and let h be the height of the available space on the paper. Then find a simple number, m_1, such that m_1 times $f_1(u'') - f_1(u')$ shall not exceed h. Similarly, find a simple number m_2 such that m_2 times $f_2(v'') - f_2(v')$ shall not exceed h.
>
> Also compute a third modulus, m_3, by the formula

$$m_3 = (m_1 m_2) / (m_1 + m_2) \qquad \text{(eq. V-3)}$$

Construction of the First Two Scales. Draw two parallel vertical axes, at any distance, k, apart. On the first axis, marked u, starting with any convenient origin, lay off the distances $x = m_1 f_1(u)$ for successive values of u, labeling each point thus plotted with the corresponding value of u. Similarly, on the second axis, marked v, starting with any convenient origin, lay off $y = m_2 f_2(v)$ for successive values of v, labeling each point with the corresponding value of v. The u-scale and the v-scale are thus completed.

Construction of the Third Scale. Draw a third line, t, parallel to the first two lines, dividing the distance, k, in the ratio m_1 / m_2; that is, the distance from u to t is $m_1 k / (m_1 + m_2)$. Compute the value t_0 corresponding to any convenient values, u_o and v_o, and label with this value, t_o, the point where the t-axis is cut by a straight line joining the points u_o and v_o. Using this point, t_o, as an anchorage, lay off along the t-line the scale determined by $z = m_3 f_3(t)$ where $m_3 = (m_1 m_2)/(m_1 + m_2)$. The third scale is thus completed, and the chart is ready for use.

Note that the units of measurement for x, y, and z must be the same. The construction of the nomograph can often be greatly facilitated by the use of previously constructed uniform and logarithmic scales with various moduli.

The relationship between the optimistic activity time estimate, the actual time required for construction, and the performance level anticipated can be related by $uv = t$, where u is the average performance level anticipated (as shown in the probability calendar), v is the optimistic time estimate, and t is the actual activity duration represented on the time chart for the period of time being questioned. By taking the logarithm of both sides, we can reduce the equation to the form $\log(u) + \log(v) = \log(t)$. Here $f_1(u) = \log(u)$, $f_2(v) = \log(v)$, and $f_3(t) = \log(t)$. For a maximum scale height of $h = 10$, and a width of $k = 5$, we may take $m_1 = 10$ where each unit represents ten percent on the efficiency scale, $m_2 = 10$ where each division represents one construction day under the expected working conditions, and, therefore, $m_3 = 5$ units, or one-half the height of scales m_1 and m_2. Since scale t is the number of days for optimal working conditions during the desired period, then m_3 must also be divided into ten units. The distance between the u and t axes and the v and t axes are computed to be equal, or 2.5 units. This procedure is sufficient to construct the nomograph in Figure V-4. If the optimistic time has been estimated, Chapter II, and the average efficiency selected from the probability calendar, Figures V-1, V-2, or V-3, then the average time that should be scheduled for that particular activity can be determined from the nomograph, Figure V-4.

Time Estimate Comparisons

Since the application of the nomograph in Figure V-4 is relatively simple, it is natural to focus our attention upon how the average time estimates derived by this method compare to the time estimates in more common usage. In particular, it is desirable to see how these times compare with the PERT method of computing activity durations.

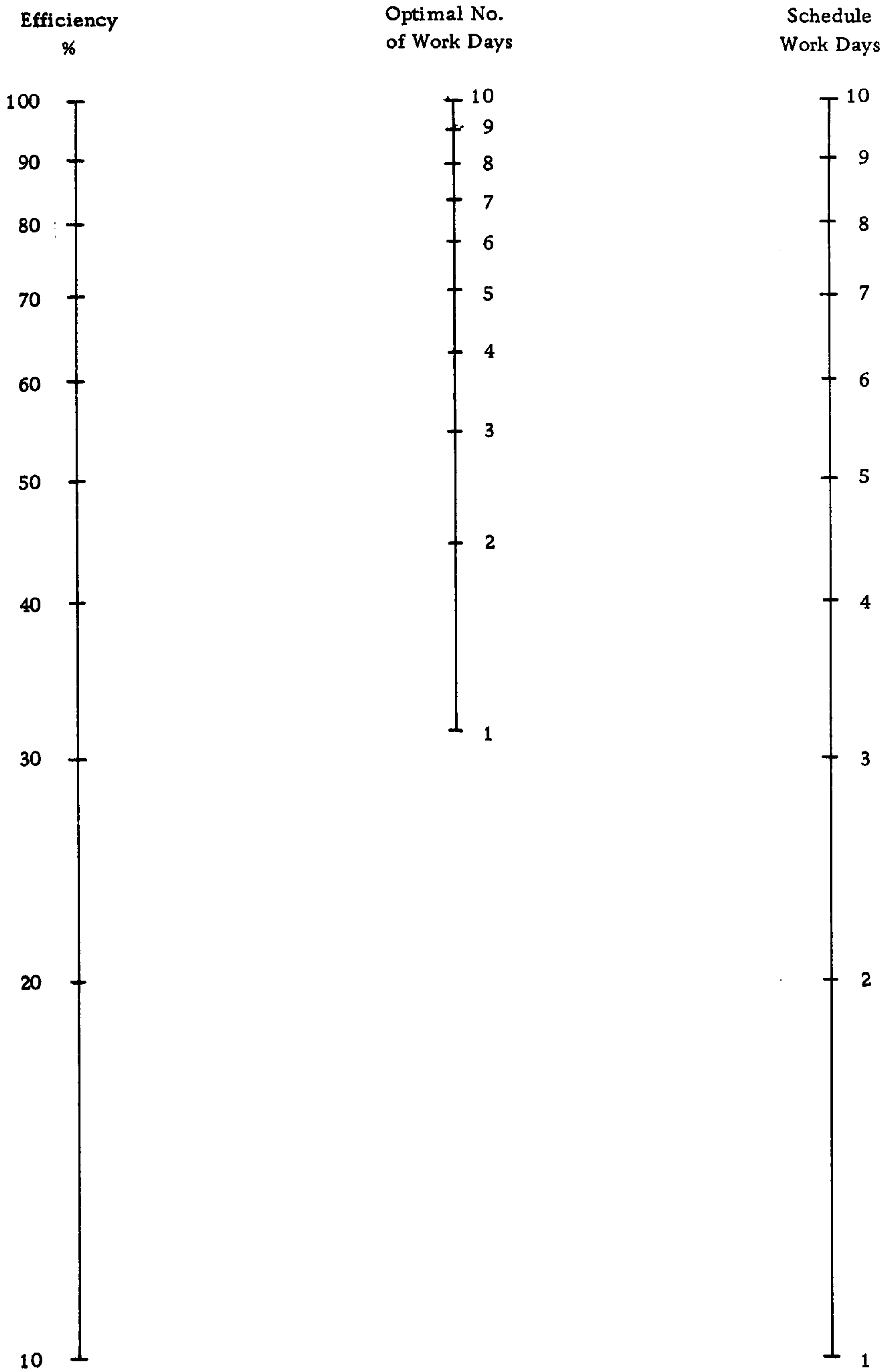


Figure V-4. Performance nomograph.

Let us again refer first to the PERT method of analysis by Moder and Phillips (19). This method is essentially the same as that normally used, the only difference being in the use of historic data to determine the normal activity time, m, and to determine $a_{.10}$ and $b_{.90}$ as follows.

R = range of sample data

= largest observation - smallest observation

k_1 = $3/d_2$, where d_2 is the statistical quality control constant tabled as a function of the number, n, of activity times in the sample data. Actually, d_2 is the average of the ratio $R/(V_{t*})^{1/2}$. Values of k_1 are given in Table V-1, and are used to compute the constants a and b.

k_2 = $k_1/2$ is used to compute $a_{.10}$ and $b_{.90}$

$\bar{t}*$ = arithmetic average of the sample data

estimate of $m = \bar{t}*$ (eq. V-4)

estimate of $a = \bar{t}* - k_1R$ or $a_{.10} = \bar{t}* - k_2R$ (eq. V-5)

estimate of $b = \bar{t}* + k_1R$ or $b_{.90} = \bar{t}* + k_2R$ (eq. V-6)

To compare the PERT and proposed CPS methods of estimating activity durations, assume that we want to schedule the placing of forms and rebar prior to the pouring of concrete for a large floor slab, Table V-3. Also, assume that this activity, based upon past experience, would normally require seven man-days to complete. For this particular activity we have only one man available, so the

Table V-1. Constant to convert the range to estimates of the standard deviation (19, p. 228).

Sample Size[a]	(Range/Std. Dev.) = d_2[b]	$k_1 = (3/d_2)$	$k_2 = (1.5/d_2)$
2	1.13	2.66	1.33
3	1.69	1.77	0.88
4	2.06	1.46	0.73
5	2.33	1.29	0.64
6	2.53	1.18	0.59
7	2.70	1.11	0.56
8	2.85	1.05	0.52
9	2.97	1.01	0.50
10	3.08	0.98	0.49
12	3.26	0.92	0.46
15	3.47	0.86	0.43
20	3.74	0.80	0.40
25	3.93	0.76	0.38

[a] Although this table includes samples as small as two, one should not rely solely on the sample data unless the sample size is at least four.

[b] The symbol d_2 used here is the universal designation of this ratio which is widely used and tabled in statistical quality control literature; it assumes the random variable is normally distributed.

activity duration will also be seven days. This particular activity requires only human labor. What amount of time should then be allowed for this activity?

First, let's determine the time estimate by means of the probability calendar, Figure V-1, and the performance nomograph, Figure V-4. Although we assumed that seven days were required to perform this activity, we may, after some deliberation, decide that under optimal conditions, only five days are required to complete this activity. This, then, is an optimistic estimate. If our original schedule indicated that we should perform this activity during the period from January 20 to January 31, we can then refer to Figure V-1 to determine the expected performance during this period. This value is approximately 61 percent. The corresponding values of $a_{.10}$ and $b_{.90}$ are 90 percent and 51 percent. From Figure V-4, using the optimistic time estimate of five days, the average activity time is read as 8.2 days by drawing a straight line from 61 percent through the optimistic time estimate of five days, to the intersection on the average time column. We can also compute the expected optimistic time of 5.6 days and the expected pessimistic time of 9.9 days by the same procedure.

Next, let us see what time estimate would have been derived using the PERT approach to estimating activity time. If we had taken a total of nine samples of activity durations according to the conditions outlined earlier, and found that the average activity time was seven days, with the best performance being five days and the worst performance being ten days, we can apply equations V-2, V-3, and V-4 and the range (R) of five days as follows.

$$m = \bar{t}^* = 7$$

$$a_{.10} = \bar{t}^* - k_2R = 7 - 0.50 \times 5 = 4.5 \text{ days}$$

$$b_{.90} = \bar{t}^* + k_2R = 7 + 0.50 \times 5 = 9.5 \text{ days}$$

$$t_e = (a_{.10} + 4m + b_{.90})/6 = (4.5 + 4 \times 7 + 9.5)/6$$

$$7.0 \text{ days}$$

Thus, the schedule time would be 7.0 days using the PERT approach as compared to 8.2 days using the new time estimate. This is a significant difference. Let us see what would happen to the critical path estimate if the activity were rescheduled for a different time in the project schedule.

Table V-2 shows the effects of performing this same activity at four different times during the year. Table V-2 then shows that it may be desirable to reschedule this activity for some other time of the year, particularly if the activity is not critical.

From Table V-2, is is easy to see that the time estimate for the activity may be near that for the PERT method at some specific times of the year. The times may also show considerable difference at other times of the year. This may be attributed to the fact that

Table V-2. Comparable activity times for four different construction dates.

Time Period	Optimal Time Estimate (man-days)	Efficiency (%)	Schedule Time (man-days)	$a_{.10}$	Time	$b_{.90}$	Time
January 20 - January 31	5	61	8.2	.90	5.6	.51	9.8
June 1 - June 10	5	86	5.8	.93	5.4	.60	8.3
August 1 - August 10	5	84	6.0	.94	5.3	.61	8.2
October 20 - October 31	5	88	5.5	.96	5.2	.70	7.2

the working conditions themselves vary throughout the year, a fact that may not be fully appreciated in the PERT analysis but which is considered by the proposed procedure for estimating activity times in critical path analysis.

Application of Historic Data

The techniques described in the previous sections are worth little if they fail to help in building a more realistic construction schedule. Unfortunately, due to a lack of time, the use of historic data as previously described has not actually been employed in a critical path analysis. The best we can do is to find a critical path analysis based on optimal or near optimal conditions with which to compare the use of historic data in the original analysis, as opposed to the actual history of the project.

The time chart in Figure V-5 was derived as part of the critical path analysis for the addition to the pharmacy building at Oregon State University. The analyst was Mr. Dan Petriquin of the Robert Wilson Construction Company, Corvallis, Oregon.

Mr. Petriquin realized from the start of the original analysis that weather was a problem that must be taken into consideration. Therefore, a total of 11 days were included during the first 66 days of the schedule to compensate for delays due to weather. How, then, does this compare with the number computed by applying historic data?

In Table V-3, the activity descriptions, along with the activity restrictions for the first part of the project, are summarized.

To apply the performance ratings to all activities would be a lengthy, time consuming process. By inspection of the activities on the activity list, it is possible to determine which activities are affected by the factors under consideration. The remaining activities may then be eliminated from further attention. It is possible to further reduce the number of activities under consideration by determining the limits of the float time required to adequately accommodate the increase in activity durations by the factors under consideration.

The first of these methods is left to the discretion of the analyzer. The second approach requires the calculation of the mean of the average efficiency ratings of the factors under consideration.

If we assume that the efficiency distribution of Figure V-1 is normally distributed, it is possible to show the effects of using a small sample size to determine the $a_{.10}$ and $b_{.90}$ limits as well as the mean value. If we let $\bar{e}*$ be the average efficiency rating and $e_{.10}$ and $e_{.90}$ be the best efficiency ratings which are not surpassed 10 times out of 100 and the worst rating which is not exceeded 10 times out of 100, then

Table V-3. Activity list and revised time estimates.

Nodes I	J	Description	Estimated Optimal Time	Average Factors	Time Days	Optimal Time a.10	Days	Pessimistic Time b.90	Days	Schedule Time
1	2	Sign Contracts	1	-	-	-	-	-	-	1
2	3	Clear Site	2	0.77	2.5	1.00	2.0	0.50	4.0	3
2	4	Fence Temporary Set-Up	7	-	-	-	-	-	-	7
2	6	Temporary Water and Electricity	3	-	-	-	-	-	-	3
2	7	Rebar Drawings and Delivery	6	-	-	-	-	-	-	6
2	29	Shop Drawings and Production Jambs	38	-	-	-	-	-	-	38
3	5	Excavate	4	0.77	5.2	1.00	4.0	0.50	8.0	9
			3	0.83	3.6	1.00	3.0	0.50	6.0	
5	8	Footings, Form, and Rebar	3	0.61	4.9	0.90	3.3	0.51	4.5	5
8	9	Concrete Pour	1	0.84	1.2	1.00	1.0	0.50	2.0	1
9	10	1st Floor Wall, Form and Rebar	5	0.81	6.1	0.94	5.2	0.58	8.7	6
11	13	Drain Tile	3	-	-	-	-	-	-	3
10	11	Concrete Pour	1	0.81	1.2	1.00	1.0	0.50	2.0	1
11	12	Stripping	3	0.90	3.3	0.96	3.1	0.64	4.5	3
11	14	Inside Gravel Fill	4	-	-	-	-	-	-	4
12	14	1st 2nd Wall, Form and	6	0.91	6.6	0.98	6.1	0.64	9.3	11
		Rebar	4	0.91	4.5	0.98	4.0	0.64	6.3	
12	30	Mechanical and Electrical Rough-In	8	-	-	-	-	-	-	8
14	15	Concrete Pour	1	0.87	1.2	1.00	1.0	0.50	2.0	1
14	16	1st Floor Set-Up	2	-	-	-	-	-	-	2
15	17	Strip Inside	3	-	-	-	-	-	-	3
16	18	Concrete Pour, Walls	1	0.88	1.2	1.00	1.0	0.50	2.0	1
18	19	2nd Floor Form	4	0.94	4.5	0.99	4.0	0.67	6.0	5
17	21	Set-Up Slab	2	-	-	-	-	-	-	2
18	21	Form and Rebar Stairs, 1 2	4	-	-	-	-	-	-	4
19	20	Rebar	2	0.94	2.2	0.99	2.1	0.68	2.9	2
19	21	Electrical and Mechanical Sleeves	2	-	-	-	-	-	-	2
20	21	Set-Up	2	-	-	-	-	-	-	2
21	22	Concrete Pour	1	0.94	1.1	1.00	1.0	0.50	2.0	1
22	23	Strip Wall	3	0.92	3.3	0.99	3.1	0.68	4.4	3
22	24	Cure, Concrete	5	-	-	-	-	-	-	5
22	27	Waterproof Foundation	4	-	-	-	-	-	-	4
23	28	Form and Rebar Walls, 2 3	6	0.86	7.0	0.96	6.3	0.66	9.1	7
24	27	Pour 3rd Floor Slab	4	0.86	4.7	0.96	4.2	0.66	6.1	5
24	26	Strip 2nd Floor Slab	3	-	-	-	-	-	-	3
24	25	Strip Stairs	1	0.86	1.2	0.96	1.1	0.66	1.7	1
25	31	Form and Rebar Stairs, 2 3	3	0.86	3.6	0.96	3.2	0.66	4.7	4

$$e_{.10} = \overline{e^*} + k_2 R \qquad \text{(eq. V-7)}$$

and

$$e_{.90} = \overline{e^*} - k_2 R \qquad \text{(eq. V-8)}$$

From Figure V-1, the range (R) is 0.95 - 0.61 = 0.34. The mean value of the average performance rating, $\overline{e^*}$, is calculated by

$$\overline{e^*} = \frac{\sum_j E_j}{N} \qquad \text{(eq. V-9)}$$

where E_j is the average performance rating for each ten day period and N is the number of ten day periods during the calendar year. Then, from Figure V-1, $\overline{e^*}$ is 0.858.

If we assume that there were ten observations in the sample size, from Table V-1, k_2 is 0.49 and $e_{.10}$ and $e_{.90}$ are 103 percent and 69 percent respectively. If there were 25 observations in the sample size, then k_2 would be 0.38, $e_{.10}$ and $e_{.90}$ would be re-computed as 86 percent and 73 percent respectively. Thus, with an increase in the sample size, it is possible to further restrict the limits of the optimal and pessimistic limits substantially.

The mean values of the average efficiency conditions for Figures V-2 and V-3 are computed as 0.892 and 0.830.

The mean values of the efficiency ratings can now be used to determine the limits for the amount of float time required for each activity under study. If only human performance is being considered, then all activities with a float time greater than 15 percent of the activity time can be eliminated from the study. These limitations can be similarly applied to equipment performance and the specific activity of concrete pouring. The values are 11 percent and 17 percent respectively. Wherever the performance ratings vary markedly from the average conditions, it may be desired to refer to the probability calendar for a more reliable estimate of the average conditions for a particular ten day period.

Using these restrictions, the activities that may be removed from further consideration in Table V-3 are so designated by placing a dash in the Performance Rating column.

It is now necessary to fill in the remainder of the Performance Rating column. This can be accomplished only as each activity is considered, one at a time, starting from the left side of the time chart in Figure V-5. The first activity is that of clearing the construction site in preparation for actual construction. This is accomplished by the use of mechanical equipment. Consequently, we need to refer to Figure V-2 to find the performance factor for the period January 11-13. This is a value of 0.77. When this factor is located on the nomograph in Figure V-4 and the estimated time of two days is also located, then it is easy to determine a schedule time of 2.5 days. The values for the optimistic and pessimistic times are also recorded.

There is still one difficulty left to consider. We have not yet

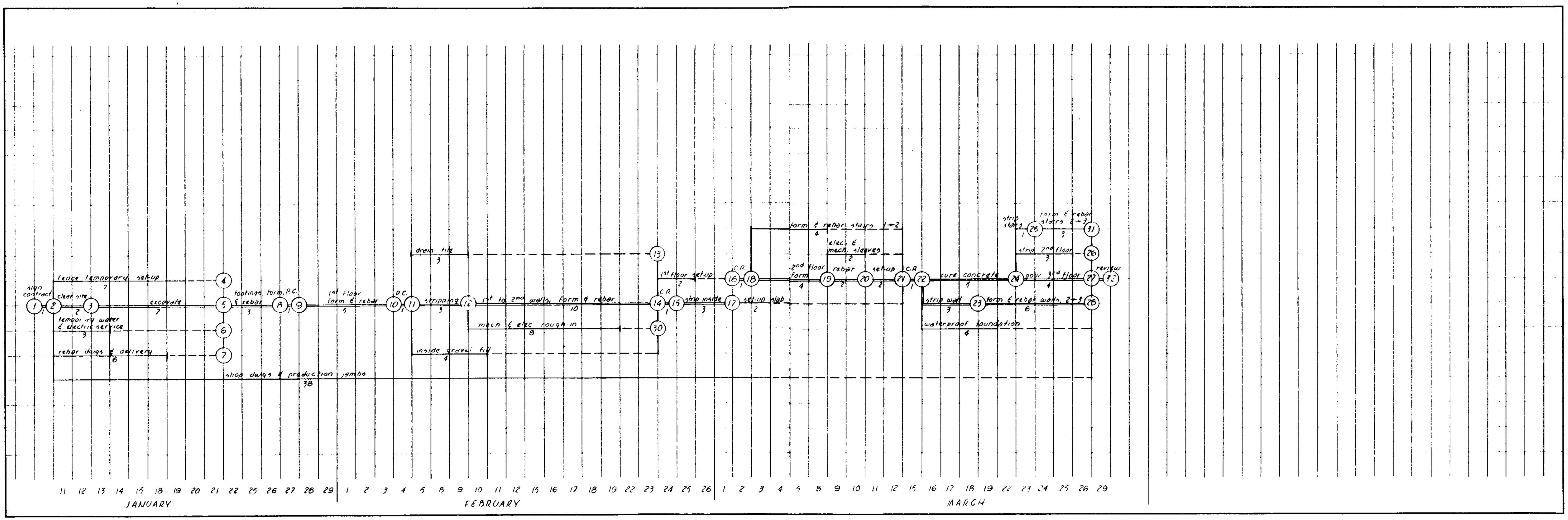


Figure V-5 Time chart for Pharmacy Building addition, Oregon State University.

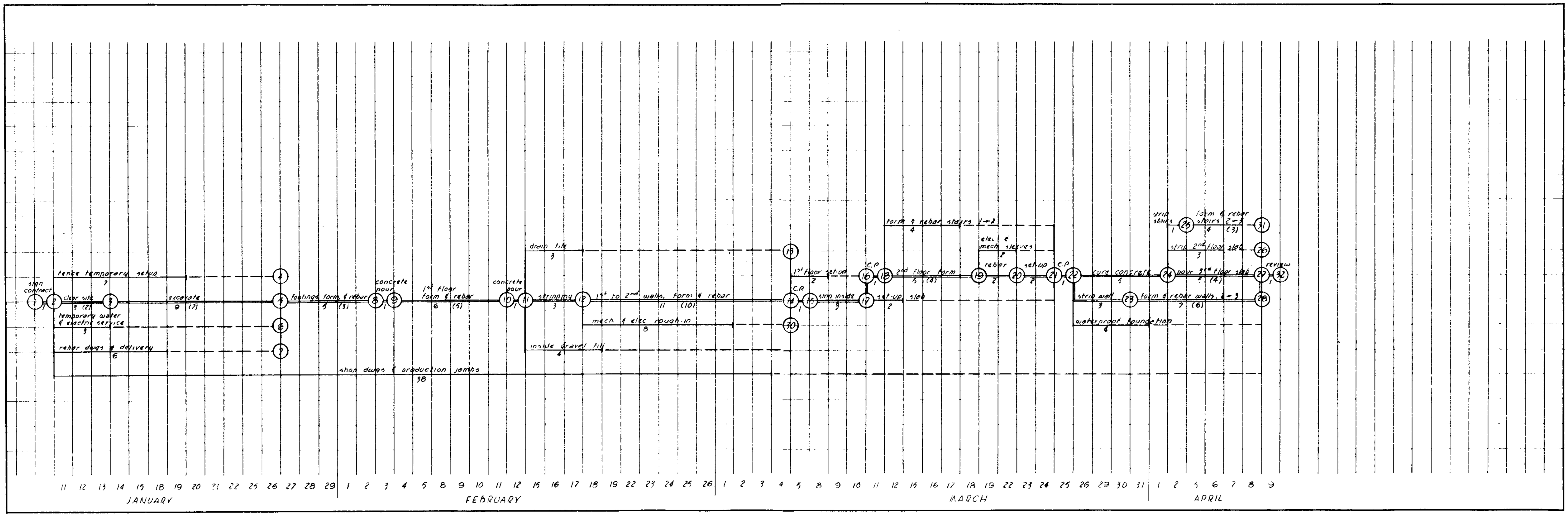


Figure V-6. Time chart for Pharmacy Building addition using revised time estimates.

discussed what to do with the fraction of the day that usually occurs when the schedule time is determined from the nomograph. Probably the easiest way to solve this problem is to refer to the optimistic and pessimistic times. This can be done with the activity clear site. The optimal time is seen to be two days, whereas the pessimistic time is four days. If the user wishes to be somewhat conservative in his estimate, he may desire to let the pessimistic time influence his thinking and round off the estimated schedule time of 2.5 days to 3.0 days. However, if he desires to be more on the optimistic side, which will probably involve a slightly higher risk of not being able to complete the activity on schedule, he may place more emphasis on the optimistic estimate of 2.0 days and round off the schedule time to 2.0 days. For our purposes we will maintain a more conservative stand and wherever the fraction is greater than 25 percent of the estimated time, or greater than 0.50, we will round off the schedule time to the next full day. These limits appear to work quite satisfactorily in actual application although there is not yet any statistical verification of these limits. It may be necessary to change these limits as more results are analysed where these techniques in estimating activity times are used.

After Table V-3 has been completed, it is necessary to go back and place the remaining activities on the time chart.

Now that the revised time chart has been completed, it is interesting to compare it with the project history. This will provide us with a way to check the assumptions that have been made with this approach to estimating activity times with a real-life situation.

The revised time chart in Figure V-6 shows us that an additional time of nine work days should be allowed for project completion. It was originally estimated by Mr. Petriquin that an additional 11 days should be allowed to compensate for the adverse affects of weather on the project efficiency. During most of the period shown on the time chart, the weather was unusually mild with a resultant high level of performance by both laborers and equipment. However, there were some activity delays due to adverse weather conditions.

During the period from January 11 to January 22 the weather permitted work to proceed at a near optimal rate. The temperatures were mild and there was little or no precipitation. Clearing of the site and the excavation work were completed two days ahead of schedule. When it came to the placing of the forms and rebar for the footings, there was a period of three days of very heavy rain which forced the curtailment of all construction activities.

Once the forms were placed, another delay was encountered. The contractor desired to pump the concrete to where the concrete was needed. The owner objected to this method and ten days were lost before this problem could be reconciled.

During the remainder of February the weather was unseasonably mild with the project efficiency remaining at a very high level.

During the first week of March the weather became less than desirable. Rains caused the scheduled concrete pour to be delayed one day. A total of two days were lost to weather during this week, the other day being to a low level of efficiency.

Mild, dry weather was characteristic for the remainder of the period shown on the time chart. As a result, not all the time allotted for the effects of weather on activity duration was required. However, the extra time was consumed by the delay due to the method of pouring concrete.

It is interesting to note that those activities for which additional time was scheduled were those which actually required the additional time as a result of the effects of weather on performance levels.

Summary

The primary objective of the probability calendars and the performance nomograph was to formulate an improved method of estimating activity durations for use in critical path scheduling.

The secondary goal was to create a computational procedure which would render the use of historic data in the CPS analysis within the realm of manual operations. After the probability calendar has been derived for the particular conditions under consideration, a minimal amount of training should enable any person to apply historic data to the CPS analysis effectively and with minimal effort.

The following steps are a suggested procedure for the application of historic data to the CPS analysis.

Compute the original time chart based upon the estimated optimistic time values.

Make an activity list of the form in Table V-3.

Determine which activities are exposed to the adverse effects of weather. Eliminate the remaining activities from further consideration.

Determine which activities have ample float time to accommodate the effects of any weather conditions that may delay completion of the activity time. Usually, if there is float time greater than 20 percent of the activity duration, this is ample time and the activity may be removed from further consideration.

Start at the left side of the time chart. For each activity affected by the weather determine the performance factor from Figures V-1, V-2, or V-3.

On the nomograph, Figure V-4, locate the estimated optimistic time and the performance factor in the appropriate columns. If the activity is scheduled to occur in two or more time periods, it will be necessary to compute the delay for each of these time periods and to add the delays to get the total delay.

If the delay is greater than one-half of a work day or if it is greater than 25 percent of a work day, consider the delay as one full work day.

For each increase in time on the critical path, shift the time axis on the time chart by an equal amount of time before the analysis of the next activity. Continue this procedure until all activities have been analysed.

If the above procedure is adhered to, then an amount of time necessary to accommodate the delays for activities due to adverse weather conditions should be included in the time chart. The additional time required for the project should then be associated with the activities effected by the weather. This would permit the contractor to estimate, or be aware of possible manpower requirements in the future that would not otherwise be considered. It can also point out the desirability to use alternate construction techniques at different times of the year.

Much work remains to be done in the area of improving time estimates for CPS analysis. It is hoped that the material presented so far will aid in reaching this goal.

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