Construction Planning

9.1 Basic Concepts in the Development of Construction Plans

Construction planning is a fundamental and challenging activity in the management and execution of construction projects. It involves the choice of technology, the definition of work tasks, the estimation of the required resources and durations for individual tasks, and the identification of any interactions among the different work tasks. A good construction plan is the basis for developing the budget and the schedule for work. Developing the construction plan is a critical task in the management of construction, even if the plan is not written or otherwise formally recorded. In addition to these technical aspects of construction planning, it may also be necessary to make organizational decisions about the relationships between project participants and even which organizations to include in a project. For example, the extent to which sub-contractors will be used on a project is often determined during construction planning.

Forming a construction plan is a highly challenging task. As Sherlock Holmes noted:

Most people, if you describe a train of events to them, will tell you what the result would be. They can put those events together in their minds, and argue from them that something will come to pass. There are few people, however, who, if you told them a result, would be able to evolve from their own inner consciousness what the steps were which led up to that result. This power is what I mean when I talk of reasoning backward. [1]

Like a detective, a planner begins with a result (i.e. a facility design) and must synthesize the steps required to yield this result. Essential aspects of construction planning include the *generation* of required activities, *analysis* of the implications of these activities, and *choice* among the various alternative means of performing activities. In contrast to a detective discovering a single train of events, however, construction planners also face the normative problem of choosing the best among numerous alternative plans. Moreover, a detective is faced with an observable result, whereas a planner must imagine the final facility as described in the plans and specifications.

In developing a construction plan, it is common to adopt a primary emphasis on either cost control or on schedule control as illustrated in Fig. 9-1. Some projects are primarily divided into expense categories with associated costs. In these cases, construction planning is cost or expense oriented. Within the categories of expenditure, a distinction is made between costs incurred directly in the performance of an activity and indirectly for the accomplishment of the project. For example, borrowing expenses for project financing and overhead items are commonly treated as indirect costs. For other projects, scheduling of work activities over time is critical and is emphasized in the planning process. In this case, the planner insures that the proper precedences among activities are maintained and that efficient scheduling of the available resources prevails. Traditional scheduling procedures emphasize the maintenance of task precedences (resulting in *critical path scheduling* procedures) or efficient use of resources over time (resulting in *job shop scheduling* procedures). Finally, most complex projects require consideration of both cost and scheduling over time, so that planning, monitoring and record keeping must consider both dimensions. In these cases, the integration of schedule and budget information is a major concern.

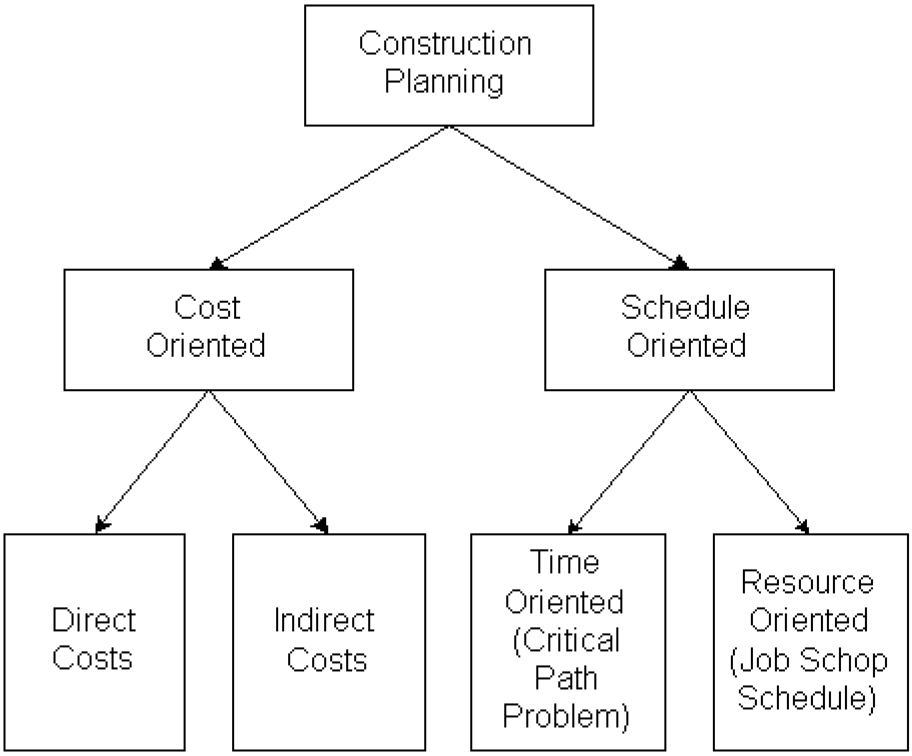

Figure 9-1 Alternative Emphases in Construction Planning

In this chapter, we shall consider the functional requirements for construction planning such as technology choice, work breakdown, and budgeting. Construction planning is not an activity which is restricted to the period after the award of a contract for construction. It should be an essential activity during the facility design. Also, if problems arise during construction, re-planning is required.

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9.2 Choice of Technology and Construction Method

As in the development of appropriate alternatives for facility design, choices of appropriate technology and methods for construction are often ill-structured yet critical ingredients in the success of the project. For example, a decision whether to pump or to transport concrete in buckets will directly affect the cost and duration of tasks involved in building construction. A decision between these two alternatives should consider the relative costs, reliabilities, and availability of equipment for the two transport methods. Unfortunately, the exact implications of different methods depend upon numerous considerations for which information may be sketchy during the planning phase, such as the experience and expertise of workers or the particular underground condition at a site.

In selecting among alternative methods and technologies, it may be necessary to formulate a number of construction plans based on alternative methods or assumptions. Once the full plan is available, then the cost, time and reliability impacts of the alternative approaches can be reviewed. This examination of several alternatives is often made explicit in bidding competitions in which several alternative designs may be proposed or *value engineering* for alternative construction methods may be permitted. In this case, potential constructors may wish to prepare plans for each alternative design using the suggested construction method as well as to prepare plans for alternative construction methods which would be proposed as part of the value engineering process.

In forming a construction plan, a useful approach is to simulate the construction process either in the imagination of the planner or with a formal computer based simulation technique. [2] By observing the result, comparisons among different plans or problems with the existing plan can be identified. For example, a decision to use a particular piece of equipment for an operation immediately leads to the question of whether or not there is sufficient access space for the equipment. Three dimensional geometric models in a computer aided design (CAD) system may be helpful in simulating space requirements for operations and for identifying any interferences. Similarly, problems in resource availability identified during the simulation of the construction process might be effectively forestalled by providing additional resources as part of the construction plan.

Example 9-1: A roadway rehabilitation

An example from a roadway rehabilitation project in Pittsburgh, PA can serve to illustrate the importance of good construction planning and the effect of technology choice. In this project, the decks on overpass bridges as well as the pavement on the highway itself were to be replaced. The initial construction plan was to work outward from each end of the overpass bridges while the highway surface was replaced below the bridges. As a result, access of equipment and concrete trucks to the overpass bridges was a considerable problem. However, the highway work could be staged so that each overpass bridge was accessible from below at prescribed times. By pumping concrete up to the overpass bridge deck from the highway below, costs were reduced and the work was accomplished much more quickly.

Example 9-2: Laser Leveling

An example of technology choice is the use of laser leveling equipment to improve the productivity of excavation and grading. [3] In these systems, laser surveying equipment is erected on a site so that the relative height of mobile equipment is known exactly. This height measurement is accomplished by flashing a rotating laser light on a level plane across the construction site and observing exactly where the light shines on receptors on mobile equipment such as graders. Since laser light does not disperse appreciably, the height at which the laser shines anywhere on the construction site gives an accurate indication of the height of a receptor on a piece of mobile equipment. In turn, the receptor height can be used to measure the height of a blade, excavator bucket

or other piece of equipment. Combined with electro-hydraulic control systems mounted on mobile equipment such as bulldozers, graders and scrapers, the height of excavation and grading blades can be precisely and automatically controlled in these systems. This automation of blade heights has reduced costs in some cases by over 80% and improved quality in the finished product, as measured by the desired amount of excavation or the extent to which a final grade achieves the desired angle. These systems also permit the use of smaller machines and less skilled operators. However, the use of these semi-automated systems require investments in the laser surveying equipment as well as modification to equipment to permit electronic feedback control units. Still, laser leveling appears to be an excellent technological choice in many instances.
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9.3 Defining Work Tasks

At the same time that the choice of technology and general method are considered, a parallel step in the planning process is to define the various work tasks that must be accomplished. These work tasks represent the necessary framework to permit *scheduling* of construction activities, along with estimating the *resources* required by the individual work tasks, and any necessary *precedences* or required sequence among the tasks. The terms work "tasks" or "activities" are often used interchangeably in construction plans to refer to specific, defined items of work. In job shop or manufacturing terminology, a project would be called a "job" and an activity called an "operation", but the sense of the terms is equivalent. [4] The *scheduling problem* is to determine an appropriate set of activity start time, resource allocations and completion times that will result in completion of the project in a timely and efficient fashion. Construction planning is the necessary fore-runner to scheduling. In this planning, defining work tasks, technology and construction method is typically done either simultaeously or in a series of iterations.

The definition of appropriate work tasks can be a laborious and tedious process, yet it represents the necessary information for application of formal scheduling procedures. Since construction projects can involve thousands of individual work tasks, this definition phase can also be expensive and time consuming. Fortunately, many tasks may be repeated in different parts of the facility or past facility construction plans can be used as general models for new projects. For example, the tasks involved in the construction of a building floor may be repeated with only minor differences for each of the floors in the building. Also, standard definitions and nomenclatures for most tasks exist. As a result, the individual planner defining work tasks does not have to approach each facet of the project entirely from scratch.

While repetition of activities in different locations or reproduction of activities from past projects reduces the work involved, there are very few computer aids for the process of defining activities. Databases and information systems can assist in the storage and recall of the activities associated with past projects as described in Chapter 14. For the scheduling process itself, numerous computer programs are available. But for the important task of defining activities, reliance on the skill, judgment and experience of the construction planner is likely to continue.

More formally, an *activity* is any subdivision of project tasks. The set of activities defined for a project should be *comprehensive* or completely *exhaustive* so that all necessary work tasks are included in one or more activities. Typically, each design element in the planned facility will have one or more associated project activities. Execution of an activity requires time and resources, including manpower and equipment, as described in the next section. The time required to perform an activity is called the *duration* of the activity. The beginning and the end of activities are signposts or *milestones*, indicating the progress of the project. Occasionally, it is useful to define activities which have no duration to mark important events. For example, receipt of equipment on the construction site may be defined as an activity since other activities would depend upon the equipment availability and the project manager might appreciate formal notice of the arrival. Similarly, receipt of regulatory approvals would also be specially marked in the project plan.

The extent of work involved in any one activity can vary tremendously in construction project plans. Indeed, it is common to begin with fairly coarse definitions of activities and then to further sub-divide tasks as the plan becomes better defined. As a result, the definition of activities evolves during the preparation of the plan. A result of this process is a natural *hierarchy* of activities with large, abstract functional activities repeatedly sub-divided into more and more specific sub-tasks. For example, the problem of placing concrete on site would have sub-activities associated with placing forms, installing reinforcing steel, pouring concrete, finishing the concrete, removing forms and others. Even more specifically, sub-tasks such as removal and cleaning of forms after concrete placement can be defined. Even further, the sub-task "clean concrete forms" could be subdivided into the various operations:

- Transport forms from on-site storage and unload onto the cleaning station.
- Position forms on the cleaning station.
- Wash forms with water.
- Clean concrete debris from the form's surface.
- Coat the form surface with an oil release agent for the next use.
- Unload the form from the cleaning station and transport to the storage location.

This detailed task breakdown of the activity "clean concrete forms" would not generally be done in standard construction planning, but it is essential in the process of programming or designing a *robot* to undertake this activity since the various specific tasks must be well defined for a robot implementation. [5]

It is generally advantageous to introduce an explicit *hierarchy* of work activities for the purpose of simplifying the presentation and development of a schedule. For example, the initial plan might define a single activity associated with "site clearance." Later, this single activity might be sub-divided into "re-locating utilities," "removing vegetation," "grading", etc. However, these activities could continue to be identified as sub-activities under the general activity of "site clearance." This hierarchical structure also facilitates the preparation of summary charts and reports in which detailed operations are combined into aggregate or "super"-activities.

More formally, a hierarchical approach to work task definition decomposes the work activity into component parts in the form of a tree. Higher levels in the tree represent decision nodes or summary activities, while branches in the tree lead to smaller components and work activities. A variety of constraints among the various nodes may be defined or imposed, including precedence relationships among different tasks as defined below. Technology choices may be *decomposed* to decisions made at particular nodes in the tree. For example, choices on plumbing technology might be made without reference to choices for other functional activities.

Of course, numerous different activity hierarchies can be defined for each construction plan. For example, upper level activities might be related to facility components such as foundation elements, and then lower level activity divisions into the required construction operations might be made. Alternatively, upper level divisions might represent general types of activities such as electrical work, while lower work divisions represent the application of these operations to specific facility components. As a third alternative, initial divisions might represent different spatial locations in the planned facility. The choice of a hierarchy depends upon the desired scheme for summarizing work information and on the convenience of the planner. In computerized databases, multiple hierarchies can be stored so that different aggregations or views of the work breakdown structure can be obtained.

The number and detail of the activities in a construction plan is a matter of judgment or convention. Construction plans can easily range between less than a hundred to many thousand defined tasks, depending on the planner's decisions and the scope of the project. If subdivided activities are too refined, the size of the network becomes unwieldy and the cost of planning excessive. Sub-division yields no benefit if reasonably accurate estimates of activity durations and the required resources cannot be made at the detailed work breakdown level. On the other hand, if the specified activities are too coarse, it is impossible to develop realistic schedules and details of resource requirements during the project. More detailed task definitions permit better control and more realistic scheduling. It is useful to define separate work tasks for:

- those activities which involve different resources, or
- those activities which do not require continuous performance.

For example, the activity "prepare and check shop drawings" should be divided into a task for preparation and a task for checking since different individuals are involved in the two tasks and there may be a time lag between preparation and checking.

In practice, the proper level of detail will depend upon the size, importance and difficulty of the project as well as the specific scheduling and accounting procedures which are adopted. However, it is generally the case that most schedules are prepared with too little detail than too much. It is important to keep in mind that task definition will serve as the basis for scheduling, for communicating the construction plan and for construction monitoring. Completion of tasks will also often serve as a basis for progress payments from the owner. Thus, more detailed task definitions can be quite useful. But more detailed task breakdowns are only valuable to the extent that the resources required, durations and activity relationships are realistically estimated for each activity. Providing detailed work task breakdowns is not helpful without a commensurate effort to provide realistic resource requirement estimates. As more powerful, computer-based scheduling and monitoring procedures are introduced, the ease of defining and manipulating tasks will increase, and the number of work tasks can reasonably be expected to expand.

Example 9-3: Task Definition for a Road Building Project

As an example of construction planning, suppose that we wish to develop a plan for a road construction project including two culverts. [6] Initially, we divide project activities into three categories as shown in Figure 9-2: structures, roadway, and general. This division is based on the major types of design elements to be constructed. Within the roadway work, a further sub-division is into earthwork and pavement. Within these subdivisions, we identify clearing, excavation, filling and finishing (including seeding and sodding) associated with earthwork, and we define watering, compaction and paving sub-activities associated with pavement. Finally, we note that the roadway segment is fairly long, and so individual activities can be defined for different physical segments along the roadway path. In Figure 9-2, we divide each paving and earthwork activity into activities specific to each of two roadway segments. For the culvert construction, we define the sub-divisions of structural excavation, concreting, and reinforcing. Even more specifically, structural excavation is divided into excavation itself and the required backfill and compaction. Similarly, concreting is divided into placing concrete forms, pouring concrete, stripping forms, and curing the concrete. As a final step in the structural planning, detailed activities are defined for reinforcing each of the two culverts. General work activities are defined for move in, general supervision, and clean up. As a result of this planning, over thirty different detailed activities have been defined.

At the option of the planner, additional activities might also be defined for this project. For example, materials ordering or lane striping might be included as separate activities. It might also be the case that a planner would define a different hierarchy of work breakdowns than that shown in Figure 9-2. For example, placing reinforcing might have been a sub-activity under concreting for culverts. One reason for separating reinforcement placement might be to emphasize the different material and resources required for this activity. Also, the division into separate roadway segments and culverts might have been introduced early in the hierarchy. With all these potential differences, the important aspect is to insure that all necessary activities are included somewhere in the final plan.

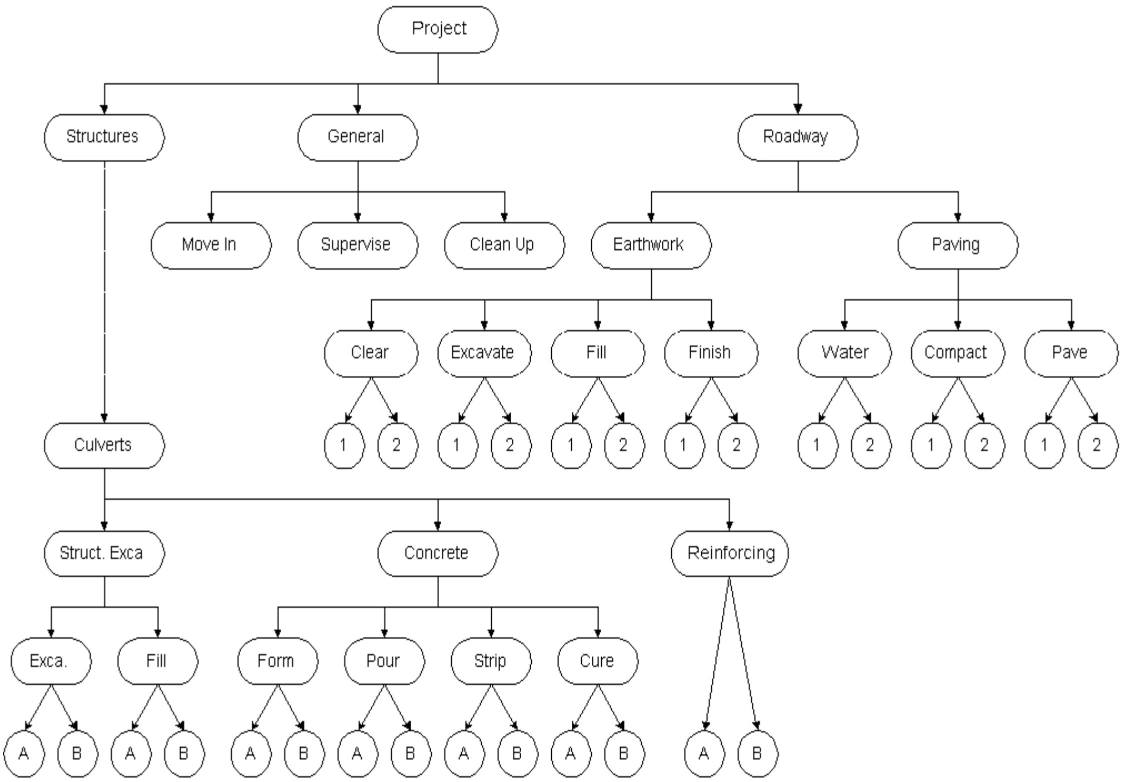

Figure 9-2 Illustrative Hierarchical Activity Divisions for a Roadway Project

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9.4 Defining Precedence Relationships Among Activities

Once work activities have been defined, the relationships among the activities can be specified. *Precedence* relations between activities signify that the activities must take place in a particular sequence. Numerous natural sequences exist for construction activities due to requirements for structural integrity, regulations, and other technical requirements. For example, design drawings cannot be checked before they are drawn. Diagramatically, precedence relationships can be illustrated by a *network* or *graph* in which the activities are represented by arrows as in Figure 9-0. The arrows in Figure 9-3 are called *branches* or *links* in the *activity network*, while the circles marking the beginning or end of each arrow are called *nodes* or *events*. In this figure, links represent particular activities, while the nodes represent milestone events.

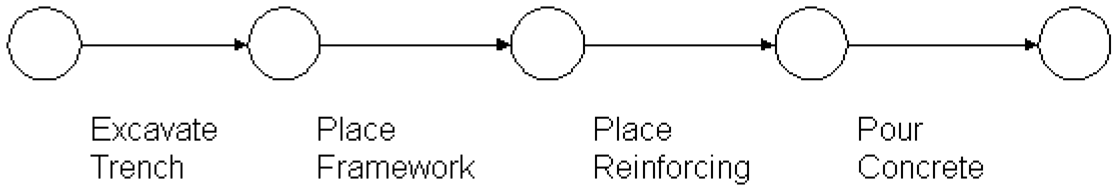

Figure 9-3 Illustrative Set of Four Activities with Precedences

More complicated precedence relationships can also be specified. For example, one activity might not be able to start for several days after the completion of another activity. As a common example, concrete might have to cure (or set) for several days before formwork is removed. This restriction on the removal of forms activity is called a *lag* between the completion of one activity (i.e., pouring concrete in this case) and the start of another activity (i.e., removing formwork in this case). Many computer based scheduling programs permit the use of a variety of precedence relationships.

Three mistakes should be avoided in specifying predecessor relationships for construction plans. First, a circle of activity precedences will result in an impossible plan. For example, if activity A precedes activity B, activity B precedes activity C, and activity C precedes activity A, then the project can never be started or completed! Figure 9-4 illustrates the resulting activity network. Fortunately, formal scheduling methods and good computer scheduling programs will find any such errors in the logic of the construction plan.

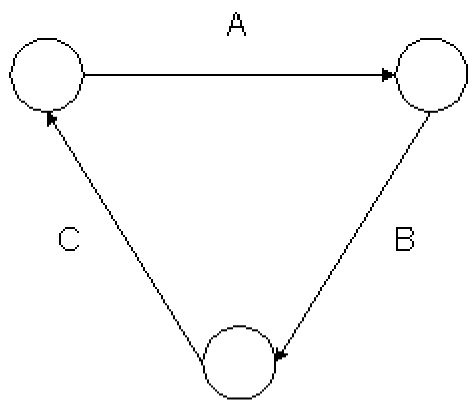

Figure 9-4 Example of an Impossible Work Plan

Forgetting a necessary precedence relationship can be more insidious. For example, suppose that installation of dry wall should be done prior to floor finishing. Ignoring this precedence relationship may result in both activities being scheduled at the same time. Corrections on the spot may result in increased costs or problems of quality in the completed project. Unfortunately, there are few ways in which precedence omissions can be found other than with checks by knowledgeable managers or by comparison to comparable projects. One other possible but little used mechanism for checking precedences is to conduct a physical or computer based simulation of the construction process and observe any problems.

Finally, it is important to realize that different types of precedence relationships can be defined and that each has different implications for the schedule of activities:

- Some activities have a necessary technical or physical relationship that cannot be superseded. For example, concrete pours cannot proceed before formwork and reinforcement are in place.
- Some activities have a necessary precedence relationship over a continuous space rather than as discrete work task relationships. For example, formwork may be placed in the first part of an excavation trench even as the excavation equipment continues to work further along in the trench. Formwork placement cannot proceed further than the excavation, but the two activities can be started and stopped independently within this constraint.
- Some "precedence relationships" are not technically necessary but are imposed due to implicit decisions within the construction plan. For example, two activities may require the same piece of equipment so a precedence relationship might be defined between the two to insure that they are not scheduled for the same time period. Which activity is scheduled first is arbitrary. As a second example, reversing the sequence of two activities may be technically possible but more expensive. In this case, the precedence relationship is not physically necessary but only applied to reduce costs as perceived at the time of scheduling.

In revising schedules as work proceeds, it is important to realize that different types of precedence relationships have quite different implications for the flexibility and cost of changing the construction plan. Unfortunately, many formal scheduling systems do not possess the capability of indicating this type of flexibility. As a result, the burden is placed upon the manager of making such decisions and insuring realistic and effective schedules. With all the other responsibilities of a project manager, it is no surprise that preparing or revising the formal, computer based construction plan is a low priority to a manager in such cases. Nevertheless, formal construction plans may be essential for good management of complicated projects.

Example 9-4: Precedence Definition for Site Preparation and Foundation Work

Suppose that a site preparation and concrete slab foundation construction project consists of nine different activities:
A. Site clearing (of brush and minor debris),
B. Removal of trees,
C. General excavation,
D. Grading general area,
E. Excavation for utility trenches,
F. Placing formwork and reinforcement for concrete,
G. Installing sewer lines,
H. Installing other utilities,
I. Pouring concrete.

Activities A (site clearing) and B (tree removal) do not have preceding activities since they depend on none of the other activities. We assume that activities C (general excavation) and D (general grading) are preceded by activity A (site clearing). It might also be the case that the planner wished to delay any excavation until trees were removed, so that B (tree removal) would be a precedent activity to C (general excavation) and D (general grading). Activities E (trench excavation) and F (concrete preparation) cannot begin until the completion of general excavation and grading, since they involve subsequent excavation and trench preparation. Activities G (install lines) and H (install utilities) represent installation in the utility trenches and cannot be attempted until the trenches are prepared, so that activity E (trench excavation) is a preceding activity. We also assume that the utilities should not be installed until grading is completed to avoid equipment conflicts, so activity D (general grading) is also preceding activities G (install sewers) and H (install utilities). Finally, activity I (pour concrete) cannot begin until the sewer line is installed and formwork and reinforcement are ready, so activities F and G are preceding. Other utilities may be routed over the slab foundation, so activity H (install utilities) is not necessarily a preceding activity for activity I (pour concrete). The result of our planning are the immediate precedences shown in Table 9-1.

TABLE 9-1 Precedence Relations for a Nine-Activity Project Example

Activity	Description	Predecessors
A	Site clearing	---
B	Removal of trees	---
C	General excavation	A
D	Grading general area	A
E	Excavation for utility trenches	B,C
F	Placing formwork and reinforcement for concrete	B,C
G	Installing sewer lines	D,E
H	Installing other utilities	D,E
I	Pouring concrete	F,G

With this information, the next problem is to represent the activities in a network diagram and to determine all the precedence relationships among the activities. One network representation of these nine activities is shown in Figure 9-5, in which the activities appear as branches or links between nodes. The nodes represent milestones of possible beginning and starting times. This representation is called an *activity-on-branch* diagram. Note that an initial event beginning activity is defined (Node 0 in Figure 9-5), while node 5 represents the completion of all activities.

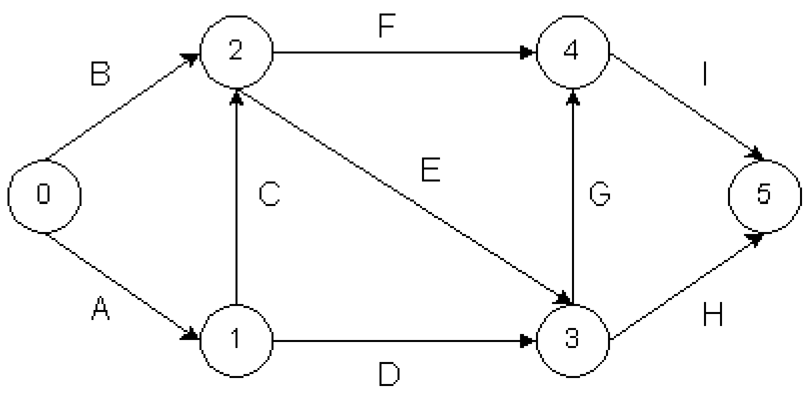

Figure 9-5 Activity-on-Branch Representation of a Nine Activity Project

Alternatively, the nine activities could be represented by nodes and predecessor relationships by branches or links, as in Figure 9-6. The result is an *activity-on-node* diagram. In Figure 9-6, new activity nodes representing the beginning and the end of construction have been added to mark these important milestones.

These network representations of activities can be very helpful in visualizing the various activities and their relationships for a project. Whether activities are represented as branches (as in Figure 9-5) or as nodes (as in Figure 9-5) is largely a matter of organizational or personal choice. Some considerations in choosing one form or another are discussed in Chapter 10.

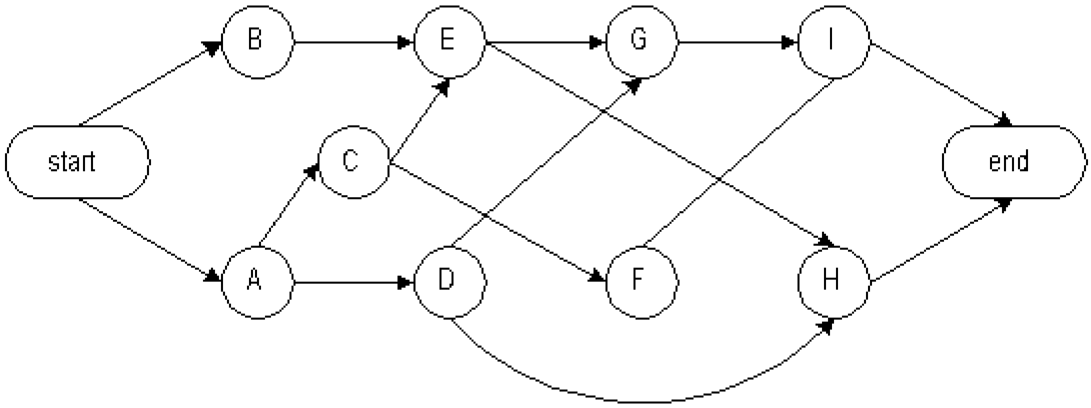

Figure 9-6 Activity-on-Node Representation of a Nine Activity Project

It is also notable that Table 9-1 lists only the *immediate* predecessor relationships. Clearly, there are other precedence relationships which involve more than one activity. For example, "installing sewer lines" (activity G) cannot be undertaken before "site clearing" (Activity A) is complete since the activity "grading general area" (Activity D) must precede activity G and must follow activity A. Table 9-1 is an *implicit* precedence list since only immediate predecessors are recorded. An explicit predecessor list would include *all* of the preceding activities for activity G. Table 9-2 shows all such predecessor relationships implied by the project plan. This table can be produced by tracing all paths through the network back from a particular activity and can be performed algorithmically. [7] For example, inspecting Figure 9-6 reveals that each activity except for activity B depends upon the completion of activity A.

TABLE 9-2 All Activity Precedence Relationships for a Nine-Activity Project

Predecessor Activity	Direct Successor Activities	All Successor Activities	All Predecessor Activities
A	C,D	E,F,G,H,I	---
B	E,F	G,H,I	---
C	E,F	G,H,I	A

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

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9.5 Estimating Activity Durations

In most scheduling procedures, each work activity has an associated time duration. These durations are used extensively in preparing a schedule. For example, suppose that the durations shown in Table 9-3 were estimated for the project diagrammed in Figure 9-0. The entire set of activities would then require at least 3 days, since the activities follow one another directly and require a total of 1.0 + 0.5 + 0.5 + 1.0 = 3 days. If another activity proceeded in *parallel* with this sequence, the 3 day minimum duration of these four activities is unaffected. More than 3 days would be required for the sequence if there was a delay or a lag between the completion of one activity and the start of another.

TABLE 9-3 Durations and Predecessors for a Four Activity Project Illustration

Activity	Predecessor	Duration (Days)
Excavate trench	---	1.0
Place formwork	Excavate trench	0.5
Place reinforcing	Place formwork	0.5
Pour concrete	Place reinforcing	1.0

All formal scheduling procedures rely upon estimates of the durations of the various project activities as well as the definitions of the predecessor relationships among tasks. The variability of an activity's duration may also be considered. Formally, the *probability distribution* of an activity's duration as well as the expected or most likely duration may be used in scheduling. A probability distribution indicates the chance that a particular activity duration will occur. In advance of actually doing a particular task, we cannot be certain exactly how long the task will require.

A straightforward approach to the estimation of activity durations is to keep historical records of particular activities and rely on the average durations from this experience in making new duration estimates. Since the scope of activities are unlikely to be identical between different projects, unit productivity rates are typically employed for this purpose. For example, the duration of an activity D_{ij} such as concrete formwork assembly might be estimated as:

(9.1) $$D_{ij} = \frac{A_{ij}}{P_{ij} N_{ij}}$$

where A_{ij} is the required formwork area to assemble (in square yards), P_{ij} is the average productivity of a standard crew in this task (measured in square yards per hour), and N_{ij} is the number of crews assigned to the task. In some organizations, unit production time, T_{ij}, is defined as the time required to complete a unit of work by a standard crew (measured in hours per square yards) is used as a productivity measure such that T_{ij} is a reciprocal of P_{ij}.

A formula such as Eq. (9.1) can be used for nearly all construction activities. Typically, the required quantity of work, A_{ij} is determined from detailed examination of the final facility design. This *quantity-take-off* to obtain the required amounts of materials, volumes, and areas is a very common process in bid preparation by contractors. In some countries, specialized quantity surveyors provide the information on required quantities for all potential contractors and the owner. The number of crews working, N_{ij}, is decided by the planner. In many cases, the number or amount of resources applied to particular activities may be modified in light of the resulting project plan and schedule. Finally, some estimate of the expected work productivity, P_{ij} must be provided to apply Equation (9.1). As with cost factors, commercial services can provide average productivity figures for many standard activities of this sort. Historical records in a firm can also provide data for estimation of productivities.

The calculation of a duration as in Equation (9.1) is only an approximation to the actual activity duration for a number of reasons. First, it is usually the case that peculiarities of the project make the accomplishment of a particular activity more or less difficult. For example, access to the forms in a particular location may be difficult; as a result, the productivity of assembling forms may be *lower* than the average value for a particular project. Often, adjustments based on engineering judgment are made to the calculated durations from Equation (9.1) for this reason.

In addition, productivity rates may vary in both systematic and random fashions from the average. An example of systematic variation is the effect of *learning* on productivity. As a crew becomes familiar with an activity and the work habits of the crew, their productivity will typically improve. Figure 9-7 illustrates the type of productivity increase that might occur with experience; this curve is called a *learning curve*. The result is that productivity P_{ij} is a function of the duration of an activity or project. A common construction example is that the assembly of floors in a building might go faster at higher levels due to improved productivity even though the transportation time up to the active construction area is longer. Again, historical records or subjective adjustments might be made to represent learning curve variations in average productivity. [8]

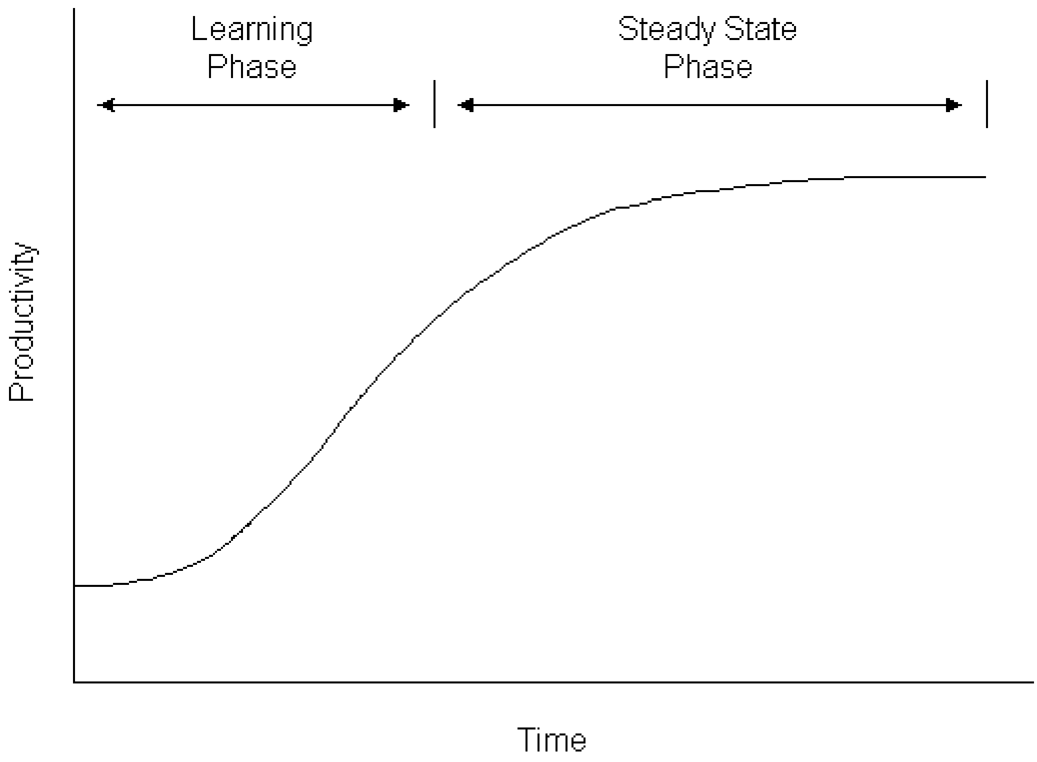

Figure 9-7 Illustration of Productivity Changes Due to Learning

Random factors will also influence productivity rates and make estimation of activity durations uncertain. For example, a scheduler will typically not know at the time of making the initial schedule how skillful the crew and manager will be that are assigned to a particular project. The productivity of a skilled designer may be many times that of an unskilled engineer. In the absence of specific knowledge, the estimator can only use average values of productivity.

Weather effects are often very important and thus deserve particular attention in estimating durations. Weather has both systematic and random influences on activity durations. Whether or not a rainstorm will come on a particular day is certainly a random effect that will influence the productivity of many activities. However, the likelihood of a rainstorm is likely to vary systematically from one month or one site to the next. Adjustment factors for inclement weather as well as meteorological records can be used to incorporate the effects of weather on durations. As a simple example, an activity might require ten days in perfect weather, but the activity could not proceed in the rain. Furthermore, suppose that rain is expected ten percent of the days in a particular month. In this case, the expected activity duration is eleven days including one expected rain day.

Finally, the use of average productivity factors themselves cause problems in the calculation presented in Equation (9.1). The expected value of the multiplicative reciprocal of a variable is not exactly equal to the reciprocal of the variable's expected value. For example, if productivity on an activity is either six in good weather (ie., P=6) or two in bad weather (ie., P=2) and good or bad weather is equally likely, then the expected productivity is P = (6)(0.5) + (2)(0.5) = 4, and the reciprocal of expected productivity is 1/4. However, the expected reciprocal of productivity is E[1/P] = (0.5)/6 + (0.5)/2 = 1/3. The reciprocal of expected productivity is 25% less than the expected value of the reciprocal in this case! By representing only two possible productivity values, this example represents an extreme case, but it is always true that the use of average productivity factors in Equation (9.1) will result in *optimistic* estimates of activity durations. The use of actual averages for the reciprocals of productivity or small adjustment factors may be used to correct for this non-linearity problem.

The simple duration calculation shown in Equation (9.1) also assumes an inverse linear relationship between the number of crews assigned to an activity and the total duration of work. While this is a reasonable assumption in situations for which crews can work independently and require no special coordination, it need not always be true. For example, design tasks may be divided among numerous architects and engineers, but delays to insure proper coordination and communication increase as the number of workers increase. As another example, insuring a smooth flow of material to all crews on a site may be increasingly difficult as the number of crews increase. In these latter cases, the relationship between activity duration and the number of crews is unlikely to be inversely proportional as shown in Equation (9.1). As a result, adjustments to the estimated productivity from Equation (9.1) must be made. Alternatively, more complicated functional relationships might be estimated between duration and resources used in the same way that nonlinear preliminary or conceptual cost estimate models are prepared.

One mechanism to formalize the estimation of activity durations is to employ a hierarchical estimation framework. This approach decomposes the estimation problem into component parts in which the higher levels in the hierarchy represent attributes which depend upon the details of lower level adjustments and calculations. For example, Figure 9-8 represents various levels in the estimation of the duration of masonry construction. [9] At the lowest level, the maximum productivity for the activity is estimated based upon general work conditions. Table 9-4 illustrates some possible maximum productivity values that might be employed in this estimation. At the next higher level, adjustments to these maximum productivities are made to account for special site conditions and crew compositions; table 9-5 illustrates some possible adjustment rules. At the highest level, adjustments for overall effects such as weather are introduced. Also shown in Figure 9-8 are nodes to estimate down or unproductive time associated with the masonry construction activity. The formalization of the estimation process illustrated in Figure 9-8 permits the development of computer aids for the estimation process or can serve as a conceptual framework for a human estimator.

TABLE 9-4 Maximum Productivity Estimates for Masonry Work

Masonry unit size	Condition(s)	Maximum produstivity achievable
8 inch block	None	400 units/day/mason
6 inch	Wall is "long"	430 units/day/mason
6 inch	Wall is not "long"	370 units/day/mason

12 inch	Labor is nonunion	300 units/day/mason
4 inch	Wall is "long" Weather is "warm and dry" or high-strength mortar is used	480 units/day/mason
4 inch	Wall is not "long" Weather is "warm and dry" or high-strength mortar is used	430 units/day/mason
4 inch	Wall is "long" Weather is not "warm and dry" or high-strength mortar is not used	370 units/day/mason
4 inch	Wall is not "long" Weather is not "warm and dry" or high-strength mortar is not used	320 units/day/mason
8 inch	There is support from existing wall	1,000 units/day/mason
8 inch	There is no support from existing wall	750 units/day/mason
12 inch	There is support from existing wall	700 units/day/mason
12 inch	There is no support from existing wall	550

TABLE 9-5 Possible Adjustments to Maximum Productivities for Masonry Construction/caption> Impact	Condition(s)	Adjustment magnitude (% of maximum)
Crew type	Crew type is nonunion Job is "large"	15%
Crew type	Crew type is union Job is "small"	10%
Supporting labor	There are less than two laborers per crew	20%
Supporting labor	There are more than two masons/laborers	10%
Elevation	Steel frame building with masonry exterior wall has "insufficient"	10%

	support labor	
Elevation	Solid masonry building with work on exterior uses nonunion labor	12%
Visibility	block is not covered	7%
Temperature	Temperature is below 45^o F	15%
Temperature	Temperature is above 45^o F	10%

Brick texture   bricks are baked high
Weather is cold or moist
bricks are baked high
Weather is cold or moist

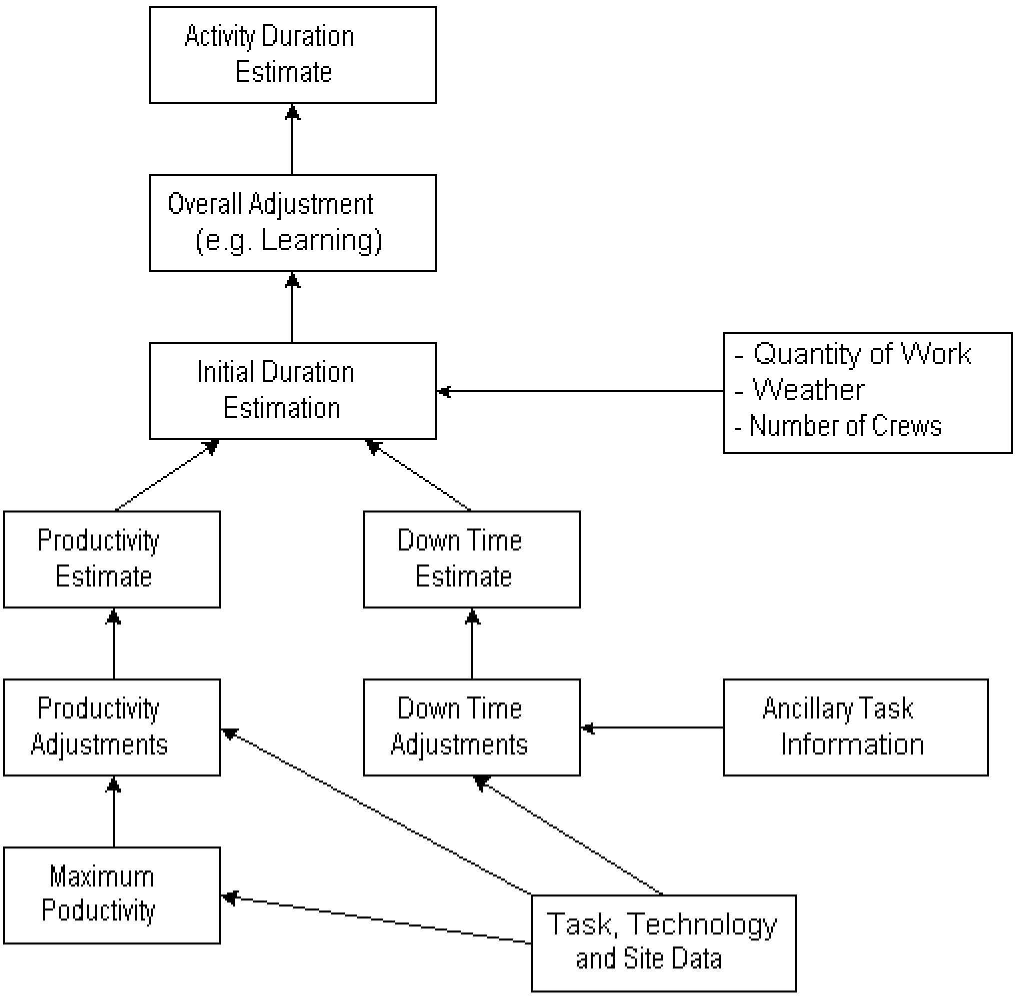

Figure 9-8 A Hierarchical Estimation Framework for Masonry Construction

In addition to the problem of estimating the expected duration of an activity, some scheduling procedures explicitly consider the uncertainty in activity duration estimates by using the probabilistic distribution of activity durations. That is, the duration of a particular activity is assu med to be a random variable that is distributed in a particular fashion. For example, an activity duration might be assumed to be distributed as a normal or a beta distributed random variable as illustrated in Figure 9-9. This figure shows the probability or chance of experiencing a particular activity duration based on a probabilistic distribution. The beta distribution is often used to characterize activity durations, since it can have an absolute minimum and an absolute maximum of possible duration times. The normal distribution is a good approximation to the beta distribution in the center of the distribution and is easy to work with, so it is often used as an approximation.

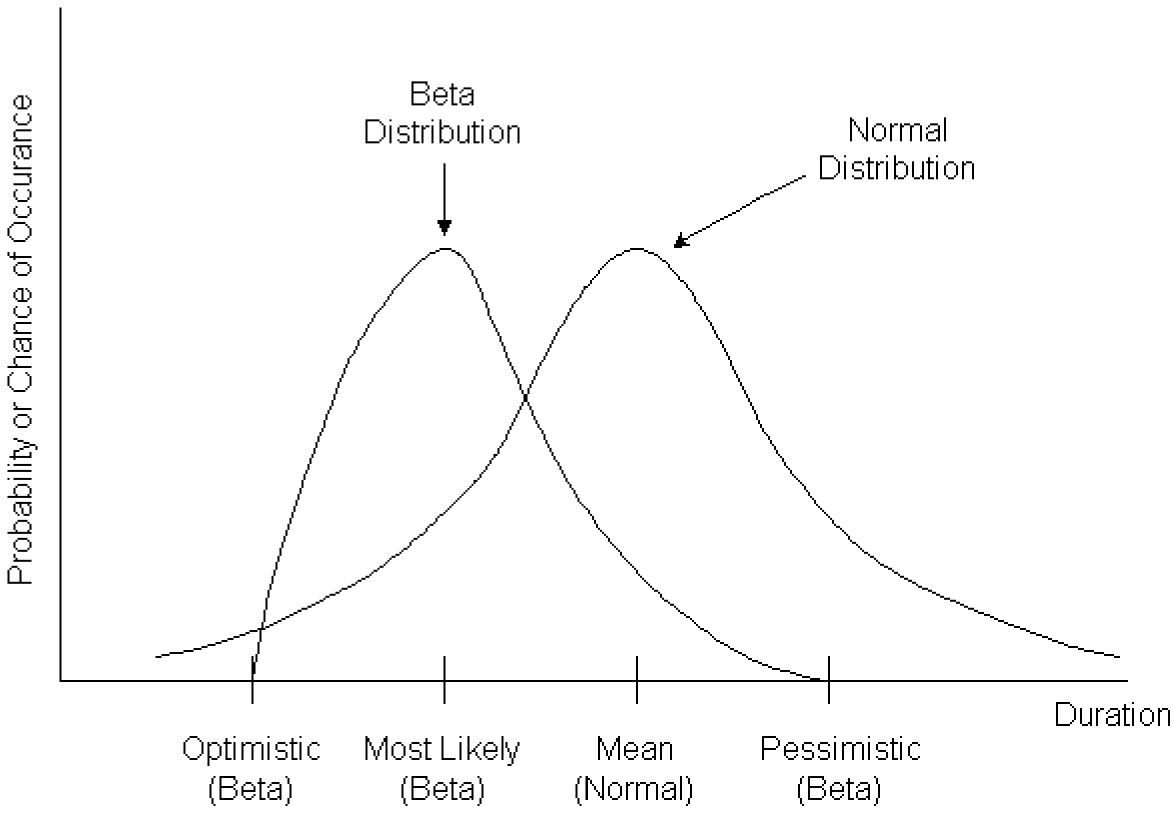

Figure 9-9 Beta and Normally Distributed Activity Durations

If a standard random variable is used to characterize the distribution of activity durations, then only a few parameters are required to calculate the probability of any particular duration. Still, the estimation problem is increased considerably since more than one parameter is required to characterize most of the probabilistic distribution used to represent activity durations. For the beta distribution, three or four parameters are required depending on its generality, whereas the normal distribution requires two parameters.

As an example, the normal distribution is characterized by two parameters, μ and σ representing the average duration and the standard deviation of the duration, respectively. Alternatively, the *variance* of the distribution σ^2 could be used to describe or characterize the variability of duration times; the variance is the value of the standard deviation multiplied by itself. From historical data, these two parameters can be estimated as:

(9.2) $$\mu \approx \bar{x} = \sum_{k=1}^{n} \frac{x_k}{n}$$

(9.3) $$\sigma^2 \approx \sum_{k=1}^{n} \frac{\left(x_k - \bar{x}\right)^2}{n-1}$$

where we assume that n different observations x_k of the random variable x are available. This estimation process might be applied to activity durations directly (so that x_k would be a record of an activity duration D_{ij} on a past project) or to the estimation of the distribution of productivities (so that x_k would be a record of the productivity in an activity P_i) on a past project) which, in turn, is used to estimate durations using Equation (9.4). If more accuracy is desired, the estimation equations for mean and standard deviation, Equations (9.2) and (9.3) would be used to estimate the mean and standard deviation of the reciprocal of productivity to avoid non-linear effects. Using estimates of productivities, the standard deviation of activity duration would be calculated as:

(9.4) $$\sigma_{ij} \approx \frac{A_{ij}\sigma_{1/P}}{N_{ij}}$$

where $\sigma_{1/P}$ is the estimated standard deviation of the reciprocal of productivity that is calculated from Equation (9.3) by substituting 1/P for x.

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9.6 Estimating Resource Requirements for Work Activities

In addition to precedence relationships and time durations, *resource requirements* are usually estimated for each activity. Since the work activities defined for a project are comprehensive, the total resources required for the project are the sum of the resources required for the various activities. By making resource requirement estimates for each activity, the requirements for particular resources during the course of the project can be identified. Potential bottlenecks can thus be identified, and schedule, resource allocation or technology changes made to avoid problems.

Many formal scheduling procedures can incorporate constraints imposed by the availability of particular resources. For example, the unavailability of a specific piece of equipment or crew may prohibit activities from being undertaken at a particular time. Another type of resource is space. A planner typically will schedule only one activity in the same location at the same time. While activities requiring the same space may have no necessary technical precedence, simultaneous work might not be possible. Computational procedures for these various scheduling problems will be described in Chapters 10 and 11. In this section, we shall discuss the estimation of required resources.

The initial problem in estimating resource requirements is to decide the extent and number of resources that might be defined. At a very aggregate level, resources categories might be limited to the amount of labor (measured in man-hours or in dollars), the amount of materials required for an activity, and the total cost of the activity. At this aggregate level, the resource estimates may be useful for purposes of project monitoring and cash flow planning. For example, actual expenditures on an activity can be compared with the estimated required resources to reveal any problems that are being encountered during the course of a project. Monitoring procedures of this sort are described in Chapter 12. However, this aggregate definition of resource use would not reveal bottlenecks associated with particular types of equipment or workers.

More detailed definitions of required resources would include the number and type of both workers and equipment required by an activity as well as the amount and types of materials. Standard resource requirements for particular activities can be recorded and adjusted for the special conditions of particular projects. As a result, the resources types required for particular activities may already be defined. Reliance on historical or standard activity definitions of this type requires a standard coding system for activities.

In making adjustments for the resources required by a particular activity, most of the problems encountered in forming duration estimations described in the previous section are also present. In particular, resources such as labor requirements will vary in proportion to the work productivity, P_{ij}, used to estimate activity durations in Equation (9.1). Mathematically, a typical estimating equation would be:

$$R_{ij}^{k} = D_{ij} N_{ij} U_{ij}^{k} \quad (9.5)$$

where R^k_{ij} are the resources of type k required by activity ij, D_{ij} is the duration of activity ij, N_{ij} is the number of standard crews allocated to activity ij, and U^k_{ij} is the amount of resource type k used per standard crew. For example, if an activity required eight hours with two crews assigned and each crew required three workers, the effort would be R = 8*2*3 = 48 labor-hours.

From the planning perspective, the important decisions in estimating resource requirements are to determine the type of technology and equipment to employ and the number of crews to allocate to each task. Clearly, assigning additional crews might result in faster completion of a particular activity. However, additional crews might result in congestion and coordination problems, so that work productivity might decline. Further, completing a particular activity earlier might not result in earlier completion of the entire project, as discussed in Chapter 10.

Example 9-5: Resource Requirements for Block Foundations

In placing concrete block foundation walls, a typical crew would consist of three bricklayers and two bricklayer helpers. If sufficient space was available on the site, several crews could work on the same job at the same time, thereby speeding up completion of the activity in proportion to the number of crews. In more restricted sites, multiple crews might interfere with one another. For special considerations such as complicated scaffolding or large blocks (such as twelve inch block), a bricklayer helper for each bricklayer might be required to insure smooth and productive work. In general, standard crew composition depends upon the specific construction task and the equipment or technology employed. These standard crews are then adjusted in response to special characteristics of a particular site.

Example 9-6: Pouring Concrete Slabs

For large concrete pours on horizontal slabs, it is important to plan the activity so that the slab for a full block can be completed continuously in a single day. Resources required for pouring the concrete depend upon the technology used. For example, a standard crew for pumping concrete to the slab might include a foreman, five laborers, one finisher, and one equipment operator. Related equipment would be vibrators and the concrete pump itself. For delivering concrete with a chute directly from the delivery truck, the standard crew might consist of a foreman, four laborers and a finisher. The number of crews would be chosen to insure that the desired amount of concrete could be placed in a single day. In addition to the resources involved in the actual placement, it would also be necessary to insure a sufficient number of delivery trucks and availability of the concrete itself.
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9.7 Coding Systems

One objective in many construction planning efforts is to define the plan within the constraints of a universal *coding system* for identifying activities. Each activity defined for a project would be identified by a pre-defined code specific to that activity. The use of a common nomenclature or identification system is basically motivated by the desire for better integration of organizational efforts and improved information flow. In particular, coding systems are adopted to provide a numbering system to replace verbal descriptions of items. These codes reduce the length or complexity of the information to be recorded. A common coding system within an organization also aids consistency in definitions and categories between projects and among the various parties involved in a project. Common coding systems also aid in the retrieval of historical records of cost, productivity and duration on particular activities. Finally, electronic data storage and retrieval operations are much more efficient with standard coding systems, as described in Chapter 14.

In North America, the most widely used standard coding system for constructed facilities is the MASTERFORMAT system developed by the Construction Specifications Institute (CSI) of the United States and Construction Specifications of Canada. [10] After development of separate systems, this combined system was originally introduced as the Uniform Construction Index (UCI) in 1972 and was subsequently adopted for use by numerous firms, information providers, professional societies and trade organizations. The term MASTERFORMAT was introduced with the 1978 revision of the UCI codes. MASTERFORMAT provides a standard identification code for nearly all the elements associated with building construction.

MASTERFORMAT involves a hierarchical coding system with multiple levels plus keyword text descriptions of each item. In the numerical coding system, the first two digits represent one of the sixteen divisions for work; a seventeenth division is used to code conditions of the contract for a constructor. In the latest version of the MASTERFORMAT, a third digit is added to indicate a subdivision within each division. Each division is further specified by a three digit extension indicating another level of subdivisions. In many cases, these subdivisions are further divided with an additional three digits to identify more specific work items or materials. For example, the code 16-950-960, "Electrical Equipment Testing" are defined as within Division 16 (Electrical) and Sub-Division 950 (Testing). The keywords "Electrical Equipment Testing" is a standard description of the activity. The seventeen major divisions in the UCI/CSI MASTERFORMAT system are shown in Table 9-6. As an example, site work second level divisions are shown in Table 9-7.

TABLE 9-6 Major Divisions in the Uniform Construction Index

0 Conditions of the contract	9 Finishes
1 General requirements	10 Specialties
2 Site work	11 Equipment
3 Concrete	12 Furnishings
4 Masonry	13 Special construction
5 Metals	14 Conveying system
6 Wood and plastics	15 Mechanical
7 Thermal and moisture prevention	16 Electrical
8 Doors and windows	

While MASTERFORMAT provides a very useful means of organizing and communicating information, it has some obvious limitations as a complete project coding system. First, more specific information such as location of work or responsible organization might be required for project cost control. Code extensions are then added in addition to the digits in the basic MASTERFORMAT codes. For example, a typical extended code might have the following elements:

0534.02220.21.A.00.cf34

The first four digits indicate the project for this activity; this code refers to an activity on project number 0534. The next five digits refer to the MASTERFORMAT secondary division; referring to Table 9-7, this activity would be 02220 "Excavating, Backfilling and Compacting." The next two digits refer to specific activities defined within this MASTERFORMAT code; the digits 21 in this example might refer to excavation of column footings. The next character refers to the *block* or general area on the site that the activity will take place; in this case, block A is indicated. The digits 00 could be replaced by a code to indicate the responsible organization for the activity. Finally, the characters cf34 refer to the particular design element number for which this excavation is intended; in this case, column footing number 34 is intended. Thus, this activity is to perform the excavation for column footing number 34 in block A on the site. Note that a number of additional activities would be associated with column footing 34, including formwork and concreting. Additional fields in the coding systems might also be added to indicate the responsible crew for this activity or to identify the specific location of the activity on the site (defined, for example, as x, y and z coordinates with respect to a base point).

As a second problem, the MASTERFORMAT system was originally designed for building construction activities, so it is difficult to include various construction activities for other types of facilities or activities associated with planning or design. Different coding systems have been provided by other organizations in particular sub-fields such as power plants or roadways. Nevertheless, MASTERFORMAT provides a useful starting point for organizing information in different construction domains.

In devising organizational codes for project activities, there is a continual tension between adopting systems that are convenient or expedient for one project or for one project manager and systems appropriate for an entire organization. As a general rule, the record keeping and communication advantages of standard systems are excellent arguments for their adoption. Even in small projects, however, ad hoc or haphazard coding systems can lead to problems as the system is revised and extended over time.

TABLE 9-7 Secondary Divisions in MASTERFORMAT for Site Work [11]

02-010 02-012 02-016	Subsurface investigation Standard penetration tests Seismic investigation
02-050 02-060 02-070 02-075 02-080	Demolition Building demolition Selective demolition Concrete removal Asbestos removal
02-100 02-110	Site preparation Site clearing Selective clearing
02-350 02-355 02-360 02-370 02-380	Piles and caissons Pile driving Driven piles Bored/augered piles Caissons
02-450	Railroad work
02-480	Marine work
02-500 02-510 02-515	Paving and surfacing Walk, road and parking paving Unit pavers Curbs

02-115 02-120	Structure moving
02-140	Dewatering
02-150	Shoring and underpinning
02-160	Excavation supporting system
02-170	Cofferdams
02-200 02-210 02-220 02-230 02-240 02-250 02-270 02-280 02-290	Earthwork Grading Excavating, backfilling and compaction Base course Soil stabilization Vibro-floatation Slope protection Soil treatment Earth dams
02-300 02-305 02-310 02-320 02-330 02-340	Tunneling Tunnel ventilation Tunnel excavating Tunnel lining Tunnel grouting Tunnel support systems

02-525 02-530 02-540 02-545 02-550 02-560 02-575 02-580	Athletic paving and surfacing Synthetic surfacing Surfacing Highway paving Airfield paving Pavement repair Pavement marking
02-600	Piped utility materials
02-660	Water distribution
02-680	Fuel distribution
02-700	Sewage and drainage
02-760	Restoration of underground pipelines
02-770	Ponds and reservoirs
02-800	Power and communications
02-880	Site improvements
02-900	Landscaping

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9.8 References

1. Baracco-Miller, E., "Planning for Construction," Unpublished MS Thesis, Dept. of Civil Engineering, Carnegie Mellon University, 1987.
2. Construction Specifications Institute, *MASTERFORMAT - Master List of Section Titles and Numbers*, Releasing Industry Group, Alexandria, VA, 1983.

3. Jackson, M.J. *Computers in Construction Planning and Control,* Allen & Unwin, London, 1986.
4. Sacerdoti, E.D. *A Structure for Plans and Behavior,* Elsevier North-Holland, New York, 1977.
5. Zozaya-Gorostiza, C., "An Expert System for Construction Project Planning," Unpublished PhD Dissertation, Dept. of Civil Engineering, Carnegie Mellon University, 1988.

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9.9 Problems

1. Develop an alternative work breakdown for the activities shown in Figure 9-2 (Example 9-3). Begin first with a spatial division on the site (i.e. by roadway segment and structure number), and then include functional divisions to develop a different hierarchy of activities.

2. Consider a cold weather structure built by inflating a special rubber tent, spraying water on the tent, letting the water freeze, and then de-flating and removing the tent. Develop a work breakdown for this structure, precedence relationships, and estimate the required resources. Assume that the tent is twenty feet by fifteen feet by eight feet tall.

3. Develop a work breakdown and activity network for the project of designing a tower to support a radio transmission antenna.

4. Select a vacant site in your vicinity and define the various activities and precedences among these activities that would be required to prepare the site for the placement of pre-fabricated residences. Use the coding system for site work shown in Table 9-7 for executing this problem.

5. Develop precedence relationships for the roadway project activities appearing in Figure 9-2 (Example 9-3).

6. Suppose that you have a robot capable of performing two tasks in manipulating blocks on a large tabletop:
    - PLACE BLOCK X ON BLOCK Y: This action places the block x on top of the block y. Preconditions for applying this action are that both block x and block y have clear tops (so there is no block on top of x or y). The robot will automatically locate the specified blocks.
    - CLEAR BLOCK X: This action removes any block from the top of block x. A necessary precondition for this action is that block x has one and only one block on top. The block removed is placed on the table top.

    For this robot, answer the following questions:

    3. Using only the two robot actions, specify a sequence of robot actions to take the five blocks shown in Figure 9-10(a) to the position shown in Figure 9-10(b) in five or six robot actions.

4. Specify a sequence of robot actions to move the blocks from position (b) to position (c) in Figure 9-10 in six moves.
5. Develop an activity network for the robot actions in moving from position (b) to position (c) in Figure 9-10. Prepare both activity-on-node and activity-on-link representations. Are there alternative sequences of activities that the robot might perform to accomplish the desired position?

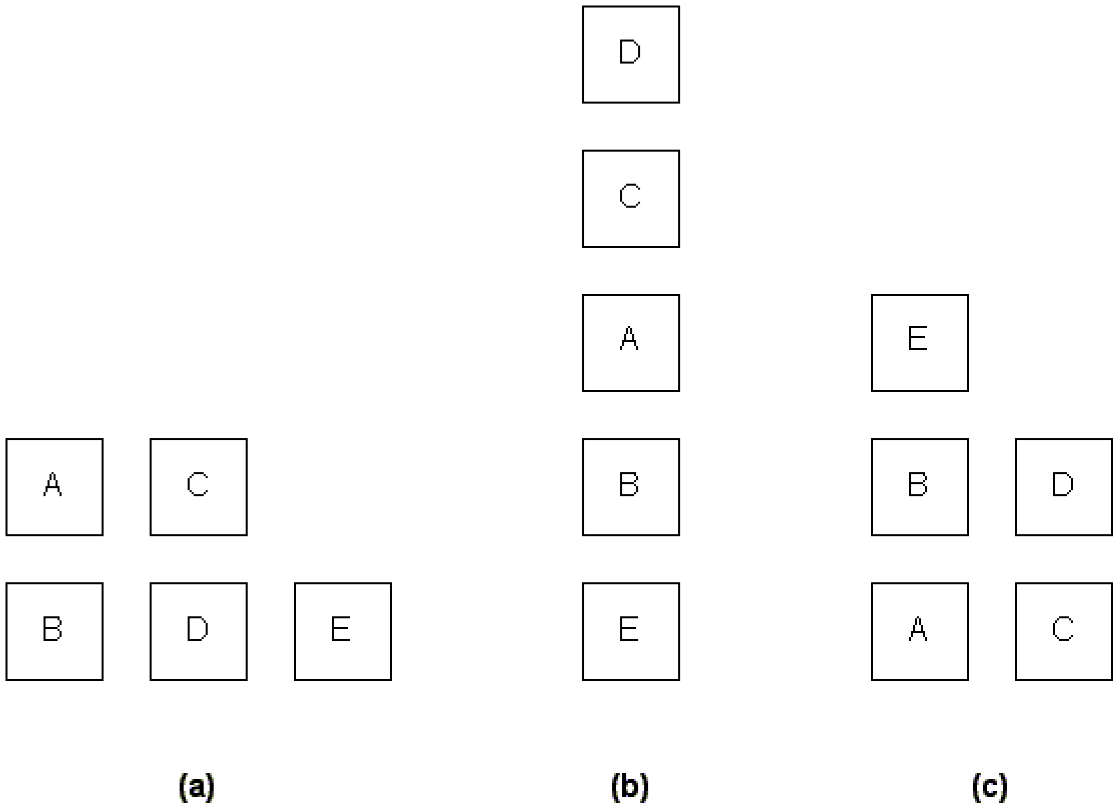

Figure 9-10 Illustrative Block Positions for Robot Motion Planning

7. In the previous problem, suppose that switching from the PLACE BLOCK action to the CLEAR BLOCK action or vice versa requires an extra ten seconds. Movements themselves require 8 seconds. What is the sequence of actions of shortest duration to go from position (b) to position (a) in Figure 9-10?

8. Repeat Problem 6 above for the movement from position (a) to position (c) in Figure 9-10.

9. Repeat Problem 7 above for the movement from position (a) to position (c) in Figure 9-10.

10. Suppose that you have an enhanced robot with two additional commands capabilities:

- CARRY BLOCKS X-Y to BLOCK Z: This action moves blocks X-Y to the top of block Z. Blocks X-Y may involve any number of blocks as long as X is on the bottom and Y is on the top. This move assumes that Z has a clear top.
- CLEAR ALL BLOCK X TO BLOCK Z: This action moves all blocks on top of block X to the top of block Z. If a block Z is not specified, then the blocks are moved to the table top.

How do these capabilities change your answer to Problems 6 and 7?

11. How does the additional capability described in Problem 10 change your answer to Problems 8 and ?

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9.10 Footnotes

1. A.C. Doyle, "A Study in Scarlet," *The Complete Sherlock Holmes*, Doubleday & Co., pg. 83, 1930. Back

2. See, for example, Paulson, B.C., S.A. Douglas, A. Kalk, A. Touran and G.A. Victor, "Simulation and Analysis of Construction Operations," *ASCE Journal of Technical Topics in Civil Engineering*, 109(2), August, 1983, pp. 89, or Carr, R.I., "Simulation of Construction Project Duration," *ASCE Journal of the Construction Division*, 105(2), June 1979, 117-128. Back

3. For a description of a laser leveling system, see Paulson, B.C., Jr., "Automation and Robotics for Construction," *ASCE Journal of Construction Engineering and Management*, (111)3, pp. 190-207, Sept. 1985. Back

4. See Baker, K.R., *Introduction to Sequencing and Scheduling*, John-Wiley and Sons, New York, 1974, for an introduction to scheduling in manufacturing. Back

5. See Skibniewski, M.J. and C.T. Hendrickson, "Evaluation Method for Robotics Implementation: Application to Concrete Form Cleaning," *Proc. Second Intl. Conf. on Robotics in Construction*, Carnegie-Mellon University, Pittsburgh, PA., 1985, for more detail on the work process design of a concrete form cleaning robot. Back

6. This example is adapted from Aras, R. and J. Surkis, "PERT and CPM Techniques in Project Management," *ASCE Journal of the Construction Division*, Vol. 90, No. CO1, March, 1964. Back

7. For a discussion of network reachability and connectivity computational algorithms, see Chapters 2 and 7 in N. Christofides, *Graph Theory: An Algorithmic Approach*, London: Academic Press, 1975, or any other text on graph theory. Back

8. See H.R. Thomas, C.T. Matthews and J.G. Ward, "Learning Curve Models of Construction Productivity," *ASCE Journal of Construction Engineering and Management*, Vol. 112, No. 2, June 1986, pp. 245-258. Back

9. For a more extension discussion and description of this estimation procedure, see Hendrickson, C., D. Martinelli, and D. Rehak, "Hierarchical Rule-based Activity Duration Estimation," *ASCE Journal of Construction Engineering and Management*, Vol 113, No. 2, 1987,pp. 288-301. Back

10. Information on the MASTERFORMAT coding system can be obtained from: The Construction Specifications Institute, 601 Madison St., Alexandria VA 22314. Back

11. Source: MASTERFORMAT: Master List of Section Titles and Numbers, 1983 Edition, The construction Speculations Institute, Alexandria, VA, 1983. Back