CHAPTER 70
DETAILED COST ESTIMATING

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70.1 THE ANATOMY OF A DETAILED ESTIMATE

The detailed cost estimating process, like the manufacture of a product, is comprised of parallel and sequential steps that flow together and interact to culminate in a completed estimate. Figure 70.1 shows the anatomy of a detailed estimate. This figure depicts graphically how the various cost estimate ingredients are synthesized from the basic man-hour estimates and material quantity estimates. Man-hour estimates of each basic skill required to accomplish the job are combined with the labor rates for these basic skills to derive labor-dollar estimates. In the meantime, material quantities are estimated in terms of the units by which they are measured or purchased, and these material quantities

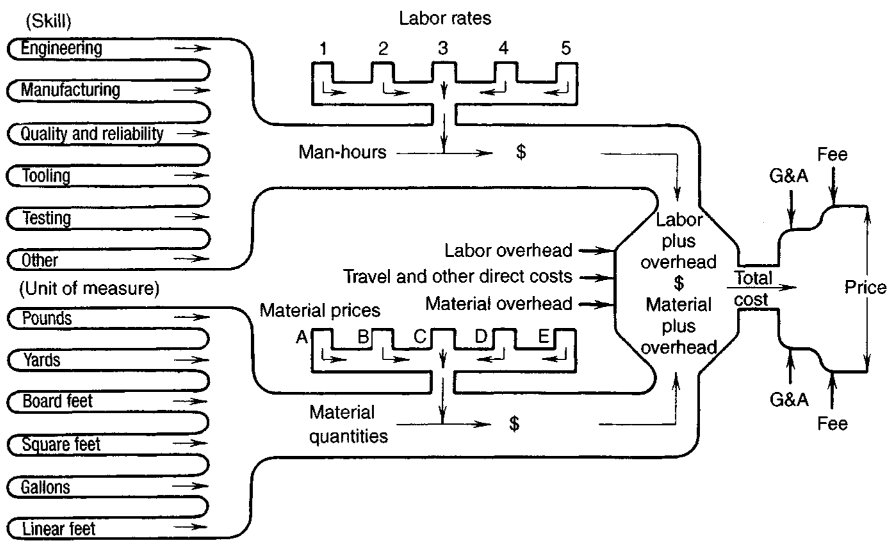

Fig. 70.1 Anatomy of an estimate.

are combined with their costs per unit to develop detailed direct material dollar estimates. Labor overhead or burden is applied to direct material costs. Then travel costs and other direct costs are added to produce total costs; general and administrative expenses and fee or profit are added to derive the "price" of the final estimate.

The labor rates applied to the basic man-hour estimates are usually "composite" labor rates; that is, they represent an average of the rates within a given skill category. For example, the engineering skill may include draftsmen, designers, engineering assistants, junior engineers, engineers, and senior engineers. The number and titles of engineering skills vary widely from company to company, but the use of a composite labor rate for the engineering skill category is common practice. The composite labor rate is derived by multiplying the labor rate for each skill by the percentage of man-hours of that skill required to do a given task and adding the results. For example, if each of the six skills have the following labor rates and percentages, the composite labor rate is computed as follows:

Skill	Labor Rate ($/h)	Percentage in the Task
Draftsman	12.00	7
Designer	16.00	3
Engineering assistant	20.00	10
Junior engineer	26.00	20
Engineer	30.00	50
Senior engineer	36.00	10
Total		100

Composite labor rate − (0.07 × $12.00) + (0.03 × $16.00) + (0.10 × $20.00) + (0.20 × $26.00) + (0.50 × $30.00) + (0.10 × $36.00) = $27.12. Similar computations can be made to obtain the composite labor rate for skills within any of the other categories.

Another common practice is to establish separate overhead or burden pools for each skill category. These burden pools carry the peripheral costs that are related to and are a function of the labor-hours expended in that particular skill category. Assuming that the burden pool is established for each of the labor skills shown in Fig. 70.1, one can write an equation to depict the entire process. This equation is shown in Fig. 70.2. Thus far we have only considered a one-element cost estimate. The addition of multi-element work activities or work outputs will greatly increase the number of mathematical computations, and it becomes readily evident that the anatomy of an estimate is so complex that computer techniques for computation are essential for all but the simplest estimate.

70.1.1 Time, Skills, and Labor-Hours Required to Prepare an Estimate

The resources (skills, calendar time, and labor-hours) required to prepare a cost estimate depend on a number of factors. One factor is the estimating method utilized. Another is the level of technology or state of the art involved in the job or task being estimated. A rule of thumb can be utilized to develop a rough idea of the estimating time required. The calendar time required to develop an accurate and credible estimate is usually about 8% of the calendar time required to accomplish a task involving existing technology and 18% for a task involving a high technology (i.e., nuclear plant construction, aerospace projects). These percentages are divided approximately as shown in Table 70.1.

Note that the largest percentage of the required estimating time is for defining the output. This area is most important because it establishes a good basis for estimate credibility and accuracy, as well as making it easier for the estimator to develop supportable labor-hour and material estimates. These percentages also assume that the individuals who are going to perform the task or who have intimate working knowledge of the task are going to assist in estimate preparation. Hence the skill mix for estimating is very similar to the skill mix required for actually performing the task.

Labor-hours required for preparation of a cost estimate can be derived from these percentages by multiplying the task's calendar period in years by 2000 labor-hours per year, multiplying the result by the percentage in Table 70.1, and then multiplying the result by 0.1 and by the number of personnel on the estimating team. Estimating team size is a matter of judgment and depends on the complexity of the task, but it is generally proportional to the skills required to perform the task (as mentioned). Examples of the application of these rules of thumb for determining the resources required to prepare a cost estimate follow:

1. A three-year, high-technology project involving 10 basic skills or disciplines would require the following number of labor-hours to estimate:

$$3 \times 2000 \times 0.18 \times 100 = 1080 \text{ labor-hours}$$

$$T = \{[(E_H \times E_R) \times (1 + E_O)] + [(M_H \times M_R) \times (1 + M_O)] + [(TO_H \times TO_R) \times (1 + TO_O)] + [(Q_H \times Q_R) \times (1 + Q_O)] + [(TE_H + TE_R) \times (1 + TE_O)] + [(O_H \times O_R) \times (1 + O_O)] + S_D + S_O + [M_D \times (1 + M_{OH})] + T_D + C_D + OD_D\} \times \{GA + 1.00\} \times \{F + 1.00\}$$

(*a*)

$$T = \{(L1_H \times L1_R) \times (1 + L1_O)] + [(L2_H \times L2_R) \times (1 + L2_O) \cdots + [(LN_H \times LN_R \times (1 + LN_O)] + S_D + S_O + [M_D \times (1 + M_{OH})] + T_D + CD + OD_D\} \times \{1 + GA\} \times \{1 \times F\}$$

where $L1, L2, \ldots LN$ are various labor rate categories

(*b*)

Symbols:

T = total cost
E_H = engineering labor hours
E_R = engineering composite labor rate in dollars per hour
E_O = engineering overhead rate in decimal form (i.e., 1.15 = 115%)
M_H = manufacturing labor hours
M_R = manufacturing composite labor rate in dollars per hour
M_O = manufacturing overhead rate in decimal form
TO_H = tooling labor hours
TO_R = tooling composite labor rate in dollars per hour
TO_O = tooling overhead in decimal form
Q_H = quality, reliability, and safety labor hours
Q_R = quality, reliability, and safety composite labor rate in dollars per hour
Q_O = quality, reliability, and safety overhead rate in decimal form
TE_H = testing labor hours
TE_R = testing composite labor rate in dollars per hour
TE_O = testing overhead rate in decimal form
O_H = other labor hours
O_R = labor rate for other hours category in dollars per hour
O_O = overhead rate for the hours category in decimal form
S_D = major subcontract dollar
S_O = other subcontract dollars
M_D = material dollars
M_{OH} = material overhead in decimal form (10% = 0.10)
T_D = travel dollars
C_D = computer dollars
OD_D = other direct dollars
GA = general and administrative expense in decimal form (25% = 0.25)
F = fee in decimal form (0.10 = 10%)

Fig. 70.2 Generalized equation for cost estimating.

Table 70.1 Estimating Time as a Percentage of Total Job Time

	Existing Technology (%)	High Technology (%)
Defining the output	4.6	14.6
Formulating the schedule and ground rules	1.2	1.2
Estimating materials and labor-hours	1.2	1.2
Estimating overhead, burden, and G&A	0.3	0.3
Estimating fee, profit, and earnings	0.3	0.3
Publishing the estimate	0.4	0.4
Total	8.0	18.0

2. A six-month "existing-technology" project requiring five skills or disciplines would require $0.6 \times 2000 \times 0.08 \times 0.1 \times 5 = 48$ labor-hours to develop an estimate.

These relationships are drawn from the author's experience in preparing and participating in cost estimates and can be relied on to give you a general guideline in preparing for the estimating process. But remember that these are "rules of thumb," and exercise caution and discretion in their application.

70.2 DISCUSSION OF TYPES OF COSTS

Detailed estimating requires the understanding of and the distinction between initial acquisition costs, fixed and variable costs, recurring and nonrecurring costs, and direct and indirect costs. These distinctions are described in the material that follows.

70.2.1 Initial Acquisition Costs

Businesspersons, consumers, and government officials are becoming increasingly aware of the need to estimate accurately and to justify the initial acquisition cost of an item to be purchased, manufactured, or built. Initial acquisition costs usually refer to the total costs to procure, install, and put into operation a piece of equipment, a product, or a structure. Initial acquisition costs do not consider costs associated with the use and possession of the item. Individuals or businesses who purchase products now give serious consideration to maintenance, operation, depreciation, energy, insurance, storage, and disposal costs before purchasing or fabricating an item, whether it be an automobile, home appliance, suit of clothes, or industrial equipment. Initial acquisition costs include planning, estimating, designing, and/or purchasing the components of the item; manufacturing, assembly, and inspection of the item; and installing and testing the item. Initial acquisition costs also include marketing, advertising, and markup of the price of the item as it flows through the distribution chain.

70.2.2 Fixed and Variable Costs

The costs of all four categories of productive outputs (processes, products, projects, and services) involve both fixed and variable costs. The relationship between fixed and variable costs depends on a number of factors, but it is principally related to the kind of output being estimated and the rate of output. Fixed cost is that group of costs involved in an ongoing activity whose total will remain relatively constant regardless of the quantity of output or the phase of the output cycle being estimated. Variable cost is the group of costs that vary in relationship to the rate of output. Therefore, where it is desirable to know the effect of output rate on costs, it is important to know the relationship between the two forms of cost as well as the magnitude of these costs. Fixed costs are meaningful only if they are considered at a given point in time, since inflation and escalation will provide a variable element to "fixed" costs. Fixed costs may only be truly fixed over a given range of outputs. Rental of floor space for a production machine is an example of a fixed cost, and its use of electrical power will be a variable cost.

70.2.3 Recurring and Nonrecurring Costs

Recurring costs are repetitive in nature and depend on continued output of a like kind. They are similar to variable costs because they depend on the quantity or magnitude of output. Nonrecurring costs are incurred to generate the very first item of output. It is important to separate recurring and nonrecurring costs if it is anticipated that the costs of continued or repeated production will be required at some future date.

70.2.4 Direct and Indirect Costs

As discussed earlier, direct costs are those that are attributable directly to the specific work activity or work output being estimated. Indirect costs are those that are spread across several projects and allocable on a percentage basis to each project. Table 70.2 is a matrix giving examples of these costs for various work outputs.

70.3 COLLECTING THE INGREDIENTS OF THE ESTIMATE

Before discussing the finer points of estimating, it is important to define the ingredients and to provide a preview of the techniques and methods utilized to collect these estimate ingredients.

70.3.1 Labor-Hours

Since the expenditure of labor-hours is the basic reason for the incurrence of costs, the estimating of labor-hours is the most important aspect of cost estimating. Labor-hours are estimated by four basic techniques: (1) use of methods, time, and measurement (MTM) techniques; (2) the labor-loading or staffing technique; (3) direct judgment of man-hours required; and (4) use of estimating handbooks. MTM methods are perhaps the most widespread methods of deriving labor-hour and skill estimates for industrial processes. These methods are available from and taught by the MTM Association for Standards and Research, located in Fair Lawn, New Jersey. The association is international in scope

Table 70.2 Examples of Costs for Various Outputs

	Process	Product	Project	Service
Initial acquisition costs	Plant construction costs	Manufacturing costs, marketing costs, and profit	Planning costs, design costs, manufacturing costs, test and checkout costs, and delivery costs	
Fixed costs	Plant maintenance costs	Plant maintenance costs	Planning costs and design costs	Building rental
Variable costs	Raw material costs	Labor costs	Manufacturing costs, test and checkout costs, and delivery costs	Labor costs
Recurring costs	Raw material costs	Labor and material costs	Manufacturing costs, test and checkout costs, and delivery costs	Labor costs
Nonrecurring costs	Plant construction costs	Plant construction costs	Planning costs and design costs	Initial capital equipment investment
Direct costs	Raw material	Manufacturing costs	Planning, design manufacturing, test and checkout and delivery costs	Labor and materials costs
Indirect costs	Energy costs	Marketing costs and profit	Energy costs	Energy costs

and has developed five generations of MTM systems for estimating all aspects of industrial, manufacturing, or machining operations. The MTM method subdivides operator motions into small increments that can be measured, and provides a means for combining the proper manual operations in a sequence to develop labor-hour requirements for accomplishing ajob.

The labor-loading or staffing technique is perhaps the simplest and most widely used method for estimating the labor-hours required to accomplish a given job. In this method, the estimator envisions the job, the work location, and the equipment or machines required, and estimates the number of people and skills that would be needed to staff a particular operation. The estimate is usually expressed in terms of a number of people for a given number of days, weeks, or months. From this staffing level, the estimated on-the-job labor-hours required to accomplish a given task can be computed.

Another method closely related to this second method is the use of direct judgment of the number of labor-hours required. This judgment is usually made by an individual who has had direct hands-on experience in either performing or supervising a like task.

Finally, the use of handbooks is a widely utilized and accepted method of developing labor-hour estimates. Handbooks usually provide larger time increments than the MTM method and require a specific knowledge of the work content and operation being performed.

70.3.2 Materials and Subcontracts

Materials and subcontract dollars are estimated in three ways: (1) drawing "takeoffs" and handbooks, (2) dollar-per-pound relationships, and (3) direct quotations or bids. The most accurate way to estimate material costs is to calculate material quantities directly from a drawing or specification of the completed product. Using the quantities required for the number of items to be produced, the appropriate materials manufacturer's handbook, and an allowance for scrap or waste, one can accurately compute the material quantities and prices. Where detailed drawings of the item to be produced are not available, a dollar-per-pound relationship can be used to determine a rough order of magnitude cost. Firm quotations or bids for the materials or for the item to be subcontracted are better than any of the previously mentioned ways of developing a materials estimate because the supplier can be held to the bid.

70.3.3 Labor Rates and Factors

The labor rate, or number of dollars required per labor-hour, is the quantity that turns a labor-hour estimate into a cost estimate; therefore, the labor rate and any direct cost factors that are added to it are key elements of the cost estimate. Labor rates vary by skill, geographical location, calendar date, and the time of day or week applied. Overtime, shift premiums, and hazardous-duty pay are also added to hourly wages to develop the actual labor rate to be used in developing a cost estimate. Wage rate structures vary considerably, depending on union contract agreements. Once the labor rate is applied to the labor-hour estimate to develop a labor cost figure, other factors are commonly used to develop other direct cost allowances, such as travel costs and direct material costs.

70.3.4 Indirect Costs, Burden, and Overhead

Burden or overhead costs for engineering activities very often are as high as 100% of direct engineering labor costs, and manufacturing overheads go to 150% and beyond. A company that can keep its overhead from growing excessively, or a company that can successfully trim its overhead, can place itself in an advantageously competitive position. Since overhead more than doubles the cost of a work activity or work output, trimming the overhead has a significant effect on reducing overall costs.

70.3.5 General and Administrative Costs

General and administrative costs range up to 20% of total direct and indirect costs for large companies. General and administrative costs are added to direct and overhead costs and are recognized as a legitimate business expense.

70.3.6 Fee, Profit, or Earnings

The fee, profit, or earnings will depend on the amount of risk the company is taking in marketing the product, the market demand for the item, and the required return on the company's investment. This subject is one that deserves considerable attention by the cost estimator. Basically, the amount of profit depends on the astute business sense of the company's management. Few companies will settle for less than 10% profit, and many will not make an investment or enter into a venture unless they can see a 20 to 30% return on their investment.

70.3.7 Assembly of the Ingredients

Once resource estimates have been accumulated, the process of reviewing, compiling, organizing, and computing the estimate begins. This process is divided into two general subdivisions of work: (1) reviewing, compiling, and organizing the input resource data, and (2) computation of the costs based on desired or approved labor rates and factors. A common mistake made in developing cost estimates is the failure to perform properly the first of these work subdivisions. In the process of reviewing, compiling, and organizing the data, duplications in resource estimates are discovered and eliminated; omissions are located and remedied; overlapping or redundant effort is recognized and adjusted; and missing or improper rationale, backup data, or supporting data are identified, corrected, or supplied. A thorough review of the cost estimate input data by the estimator or estimating team, along with an adjustment and reconciliation process, will accomplish these objectives.

Computation of a cost estimate is mathematically simple since it involves only multiplication and addition. The number of computations can escalate rapidly, however, as the number of labor skills, fiscal years, and work breakdown structure elements are increased. One who works frequently in industrial engineering labor hour and material-based cost estimating will quickly come to the conclusion that some form of computer assistance is required.

With the basic ingredients and basic tools available, we are now ready to follow the steps required to develop a good detailed cost estimate. All steps are needed for any good cost estimate. The manner of accomplishing each step, and the depth of information needed and time expended on each step, will vary considerably, depending on what work activity or work output is being estimated. These steps are as follows:

1. Develop the work breakdown structure.
2. Schedule the work elements.
3. Retrieve and organize historical cost data.
4. Develop and use cost estimating relationships.
5. Develop and use production learning curves.

6. Identify skill categories, levels, and rates.
7. Develop labor-hour and material estimates.
8. Develop overhead and administrative costs.
9. Apply inflation and escalation factors.
10. Price (compute) the estimated costs.
11. Analyze, adjust, and support the estimate.
12. Publish, present, and use the estimate.

70.4 THE FIRST QUESTIONS TO ASK (AND WHY)

Whether you are estimating the cost of a process, product, or service, there are some basic questions you must ask to get started on a detailed cost estimate. These questions relate principally to the requirements, descriptions, location, and timing of the work.

70.4.1 What Is It?

A surprising number of detailed cost estimates fail to be accurate or credible because of a lack of specificity in describing the work that is being estimated. The objectives, ground rules, constraints, and requirements of the work must be spelled out in detail to form the basis for a good cost estimate. First, it is necessary to determine which of the four generic work outputs (process, product, project, or service) or combination of work outputs best describe the work being estimated. Then it is necessary to describe the work in as much detail as possible.

70.4.2 What Does It Look Like?

Work descriptions usually take the form of detailed specifications, sketches, drawings, materials lists, and parts lists. Weight, size, shape, material type, power, accuracy, resistance to environmental hazards, and quality are typical factors that are described in detail in a specification. Processes and services are usually defined by the required quality, accuracy, speed, consistency, or responsiveness of the work. Products and projects, on the other hand, usually require a preliminary or detailed design of the item or group of items being estimated. In general, more detailed designs will produce more accurate cost estimates. The principal reason for this is that as a design proceeds, better definitions and descriptions of all facets of this design unfold. The design process is an interactive one in which component or subsystem designs proceed in parallel; component or subsystem characteristics reflect on and affect one another to alter the configuration and perhaps even the performance of the end item. Another reason that a more detailed design results in a more accurate and credible cost estimate is that the amount of detail itself produces a greater awareness and visibility of potential inconsistencies, omissions, duplications, and overlaps.

70.4.3 When Is It to Be Available?

Production rate, production quantity, and timing of production initiation and completion are important ground rules to establish before starting a cost estimate. Factors such as raw material availability, labor skills required, and equipment utilization often force a work activity to conform to a specific time period. It is important to establish the optimum time schedule early in the estimating process, to establish key milestone dates, and to subdivide the overall work schedule into identifiable increments that can be placed on a calendar time scale. A work output schedule placed on a calendar time scale will provide the basic inputs needed to compute start-up costs, fiscal-year funding, and inflationary effects.

70.4.4 Who Will Do It?

The organization or organizations that are to perform an activity, as well as the skill categories and skill levels within these organizations, must be known or assumed to formulate a credible cost estimate. Given a competent organization with competent employees, another important aspect of developing a competitive cost estimate is the determination of the make or buy structure and the skill mix needs throughout the time period of a work activity. Judicious selection of the performers and wise time phasing of skill categories and skill levels can rapidly produce prosperity for any organization with a knowledge of its employees, its products, and its customers.

70.4.5 Where Will It Be Done?

Geographical factors have a strong influence on the credibility and competitive stature of a cost estimate. In addition to the wide variation in labor costs for various locations, material costs vary substantially from location to location, and transportation costs are entering even more heavily into the cost picture than in the past. The cost estimator must develop detailed ground rules and assumptions concerning location of the work, and then estimate costs accurately in keeping with all location-oriented factors.

70.5 THE ESTIMATE SKELETON: THE WORK BREAKDOWN STRUCTURE

The first step in developing a cost estimate of any type of work output is the development of a work breakdown structure. The work breakdown structure serves as a framework for collecting, accumulating, organizing, and computing the direct and directly related costs of a work activity or work output. It also can be and usually is utilized for managing and reporting resources and related costs throughout the lifetime of the work. There is considerable advantage in using the work breakdown structure and its accompanying task descriptions as the basis for scheduling, reporting, tracking, and organizing, as well as for initial costing. Hence it is important to devote considerable attention to this phase of the overall estimating process. A work breakdown structure is developed by subdividing a process, product, project, or service into its major work elements, then breaking the major work elements into subelements, and subelements into sub-subelements, and so on. There are usually 5 to 10 subelements under each major work element.

The purpose of developing the work breakdown structure is fivefold:

1. To provide a lower-level breakout of small tasks that are easy to identify, man-load, schedule, and estimate
2. To ensure that all required work elements are included in the work output
3. To reduce the possibility of overlap, duplication, or redundancy of tasks
4. To furnish a convenient hierarchical structure for the accumulation of resource estimates
5. To give greater overall visibility as well as depth of penetration into the makeup of any work activity

70.6 THE HIERARCHICAL RELATIONSHIP OF A DETAILED WORK BREAKDOWN STRUCTURE

A typical work breakdown structure is shown in Fig. 70.3. Note that the relationship resembles a hierarchy where each activity has a higher activity, parallel activities, and lower activities. A basic principle of work breakdown structures is that the resources or content of each work breakdown are made up of the sum of the resources or content of elements below it. No work element that has lower elements exceeds the sum of those lower elements in resource requirements. The bottommost elements are estimated at their own level and sum to higher levels. Many numbering systems are feasible and workable. The numbering system utilized here is one that has proved workable in a wide variety of situations.

One common mistake in using work breakdown structures is to try to input or allocate effort to every element, even those at a higher level. Keep in mind that this should not be done because each block or work element contains only that effort included in those elements *below* it. If there are no elements below it, then it can contain resources. If there is need to add work activities or resources not included in a higher-level block, add an additional block below it to include the desired effort. Level 1 of a work breakdown structure is usually the top level, with lower levels numbered sequentially as shown. The "level" is usually equal to the number of digits in the work element block. For example, the block numbered 1.1.3.2 is in level 4 because it contains four digits.

70.7 FUNCTIONAL ELEMENTS DESCRIBED

When subdividing a work activity or work output into its elements, the major subdivisions can be either functional or physical elements. The second level in a work breakdown structure usually consists of a combination of functional and physical elements if a product or project is being estimated. For a process or service, all second-level activities could be functional. Functional elements of a production or project activity can include activities such as planning, project management, systems engineering and integration, testing, logistics, and operations. A process or service can include any of hundreds of functional elements. Typical examples of the widely dispersed functional elements that can be found in a work breakdown structure for a service are advising, assembling, binding, cleaning, fabricating, inspecting, packaging, painting, programming, receiving, testing, and welding.

70.8 PHYSICAL ELEMENTS DESCRIBED

The physical elements of a work output are the physical structures, hardware, products, or end items that are supplied to the consumer. These physical elements represent resources because they require labor and materials to produce. Hence they can and should be a basis for the work breakdown structure.

Figure 70.4 shows a typical work breakdown structure of just the physical elements of a well-known consumer product, the automobile. The figure shows how just one automobile company chose to subdivide the components of an automobile. For any given product or project, the number of ways that a work breakdown structure can be constructed are virtually unlimited. For example, the company

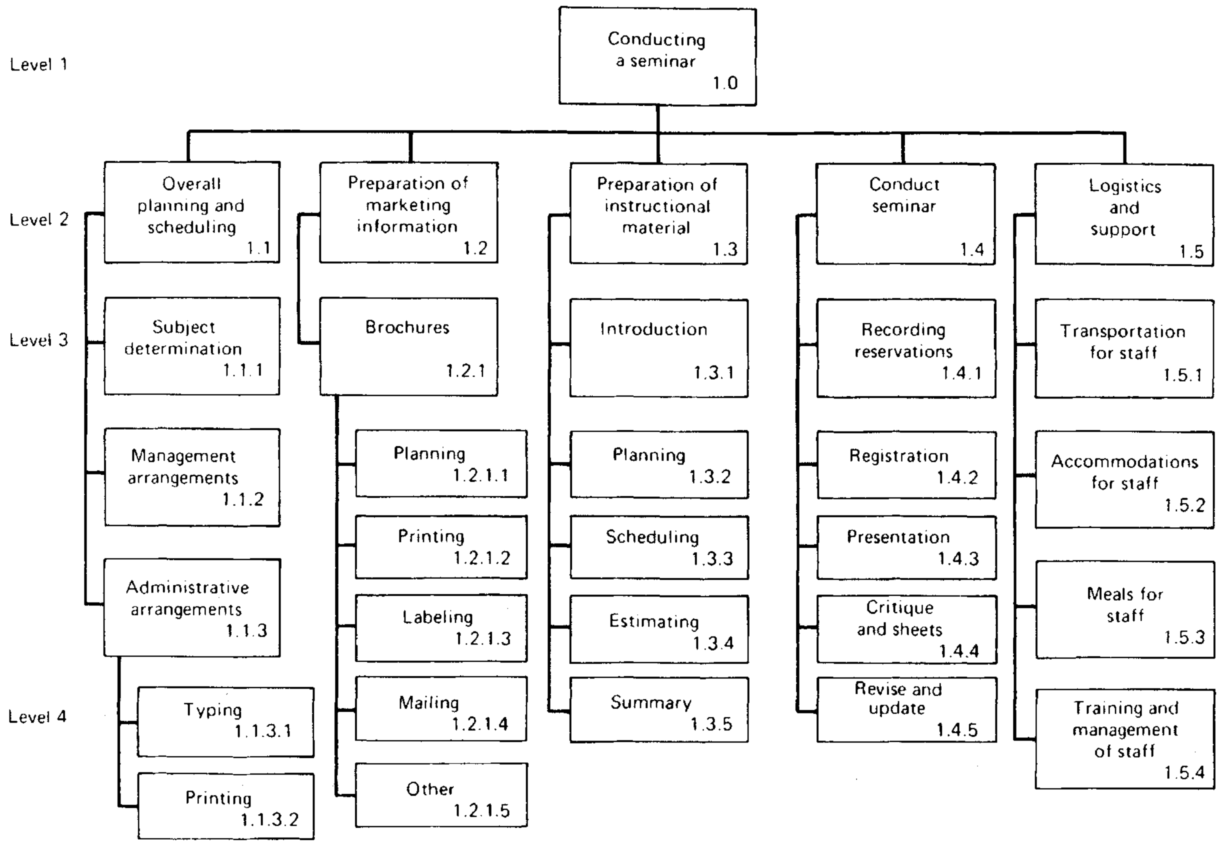

Fig. 70.3 Typical work breakdown structure.

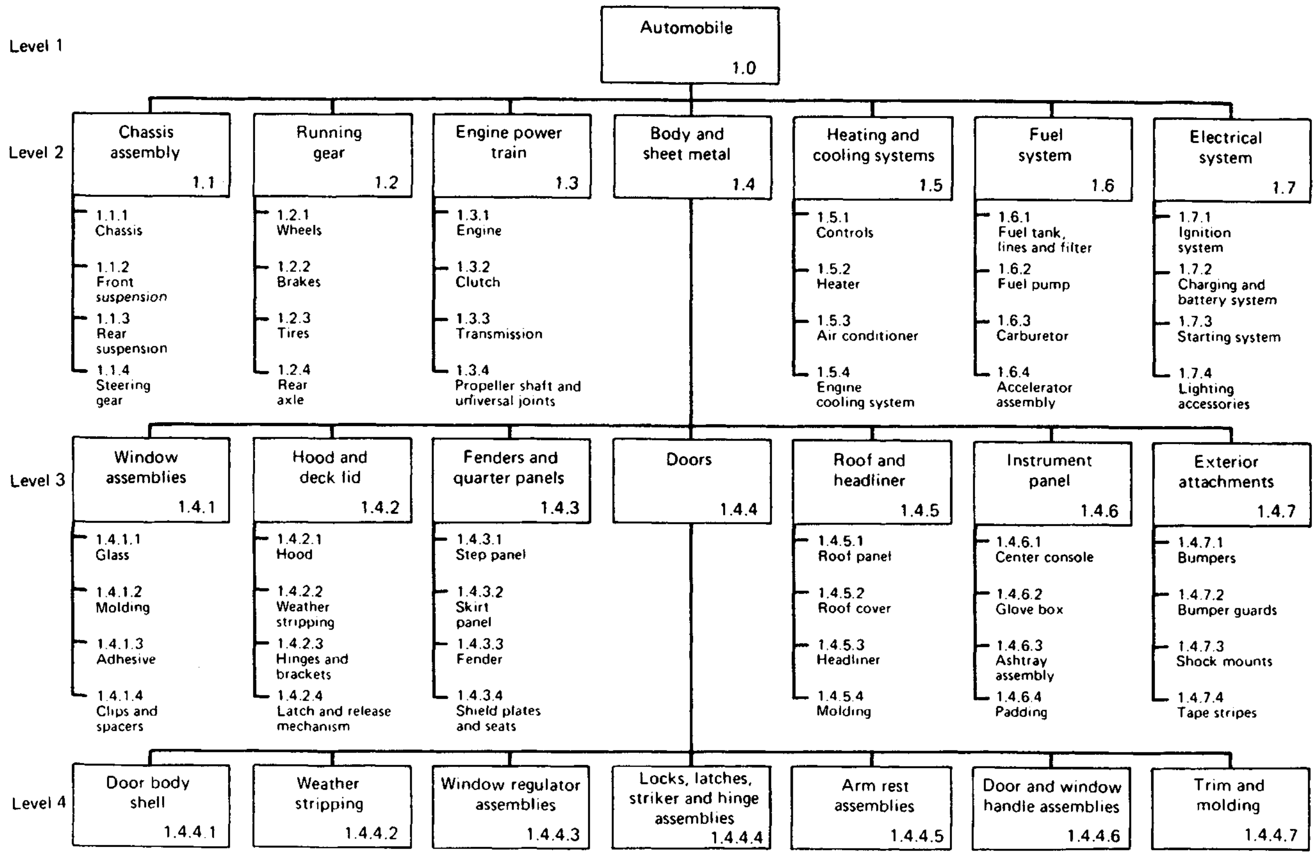

Fig. 70.4 Work breakdown structure of an automobile.

could have included the carburetor and engine cooling system as part of the engine assembly (this might have been a more logical and workable arrangement since it is used in costing a mass-production operation). Note that the structure shows a level-3 breakout of the body and sheet metal element, and the door (a level-3 element) is subdivided into its level-4 components.

This *physical element* breakout demonstrates several important characteristics of a work breakdown structure. First, note that level 5 would be the individual component parts of each assembly or subassembly. It only took three subdivisions of the physical hardware to get down to a point where the next level breakout would be the individual parts. One can see rapidly that breaking down every level-2 element three more levels (down to level 5) would result in a very large work breakdown structure. Second, to convert this physical hardware breakout into a true work breakdown structure would require the addition of some functional activities. To provide the manpower as well as the materials required to procure, manufacture, assemble, test, and install the components of each block, it is necessary to add an "assembly," "fabrication," or "installation" activity block.

70.9 TREATMENT OF RECURRING AND NONRECURRING ACTIVITIES

Most work consists of both nonrecurring activities, or "one-of-a-kind" activities needed to produce an item or to provide a service, and recurring or repetitive activities that must be performed to provide more than one output unit. The resources requirements (labor-hours and materials) necessary to perform these nonrecurring and recurring activities reflect themselves in nonrecurring and recurring costs.

Although not all estimates require the separation of nonrecurring and recurring costs, it is often both convenient and necessary to separate costs because one may need to know what the costs are for an increased work output rate. Since work output rate principally affects the recurring costs, it is desirable to have these costs readily accessible and identifiable.

Separation of nonrecurring and recurring costs can be done in two ways that are compatible with the work breakdown structure concept. First, the two costs can be identified, separated, and accounted for within each work element. Resources for each task block would, then, include three sets of resource estimates: (1) nonrecurring costs, (2) recurring costs, and (3) total costs for that block. The second convenient method of cost separation is to start with identical work breakdown structures for both costs, and develop two separate cost estimates. A third estimate, which sums the two cost estimates into a total, can also use the same basic work breakdown structure. If there are elements unique to each cost category, they can be added to the appropriate work breakdown structure.

70.10 WORK BREAKDOWN STRUCTURE INTERRELATIONSHIPS

As shown in the automobile example, considerable flexibility exists concerning the placement of physical elements (the same is true with functional elements) in the work breakdown structure. Because of this, and because it is necessary to define clearly where one element leaves off and the other takes over, it is necessary to provide a detailed definition of what is included in each work activity block. In the automotive example, the rear axle unit could have been located and defined as part of the power train or as part of the chassis assembly rather than as part of the running gear. Where does the rear axle leave off and the power train begin? Is the differential or part of the differential included in the power train? These kinds of questions must be answered—and they usually are answered—before a detailed cost estimate is generated, in the form of a work breakdown structure dictionary. The dictionary describes exactly what is included in each work element and what is excluded; it defines where the interface is located between two work elements; and it defines where the assembly effort is located to assemble or install two interfacing units.

A good work breakdown structure dictionary will prevent many problems brought about by overlaps, duplications, and omissions, because detailed thought has been given to the interfaces and content of each work activity.

70.10.1 Skill Matrix in a Work Breakdown Structure

When constructing a work breakdown structure, keep in mind that each work element will be performed by a person or group of people using one or more skills. There are two important facets of the labor or work activity for each work element: skill mix and skill level. The skill mix is the proportion of each of several skill categories that will be used in performing the work. *Skill categories* vary widely and depend on the type of work being estimated. For a residential construction project, for example, typical skills would be bricklayer, building laborer, carpenter, electrician, painter, plasterer, or plumber. Other typical construction skills are structural steelworker, cement finisher, glazier, roofer, sheet metal worker, pipefitter, excavation equipment operator, and general construction laborer. Professional skill categories such as lawyers, doctors, financial officers, administrators, project managers, engineers, printers, writers, and so forth are called on to do a wide variety of direct-labor activities. Occasionally, skills will be assembled into several broad categories (such as engineering, manufacturing, tooling, testing, and quality assurance) that correspond to overhead or burden pools.

Skill level, on the other hand, depicts the experience or salary level of an individual working within a given skill category. For example, engineers are often subdivided into various categories such as principal engineers, senior engineers, engineers, associate engineers, junior engineers, and engineering technicians. The skilled trades are offen subdivided into skill levels and given names that depict their skill level; for example, carpenters could be identified as master carpenters, journeymen, apprentices, and helpers. Because skill categories and skill levels are designated for performing work within each work element, it is not necessary to establish separate work elements for performance of each skill. A work breakdown structure for home construction would not have an element designated *carpentry,* because carpentry is a skill needed to perform one or more of the work elements (i.e., roof construction, wall construction).

70.10.2 Organizational Relationships to a Work Breakdown Structure

Frequently all or part of a work breakdown structure will have a direct counterpart in the performing organization. Although it is not necessary for the work breakdown structure to be directly correlatable to the organizational structure, it is often convenient to assign the responsibility for estimating and for performing a specific work element to a specific organizational segment. This practice helps to motivate the performer, since it assigns responsibility for an identifiable task, and it provides the manager greater assurance that each part of the work will be accomplished. In the planning and estimating process, early assignment of work elements to those who are going to be responsible for performing the work will motivate them to do a better job of estimating and will provide greater assurance of completion of the work within performance, schedule, and cost constraints, because the functional organizations have set their own goals. Job performance and accounting for work accomplished versus funds spent can also be accomplished more easily if an organizational element is held responsible for a specific work element in the work breakdown structure.

70.11 METHODS USED WITHIN THE DETAILED ESTIMATING PROCESS

The principal methods used *within* the detailed estimating process are detailed resource estimating, direct estimating, estimating by analogy, firm quotes, handbook estimating, and the parametric estimating technique mentioned earlier. These methods are described briefly in the following sections.

70.11.1 Detailed Resource Estimating

Detailed resource estimating involves the synthesis of a cost estimate from resource estimates made at the lowest possible level in the work breakdown structure. Detailed estimating presumes that a detailed design of the product or project is available and that a detailed manufacturing, assembly, testing, and delivery schedule is available for the work. This type of estimating assumes that skills, labor-hours, and materials can be identified for each work element through one or more of the methods that follow. A detailed estimate is usually developed through a synthesis of work element estimates developed by various methods.

70.11.2 Direct Estimating

A direct estimate is a judgmental estimate made in a "direct" method by an estimator or performer who is familiar with the task being estimated. The estimator will observe and study the task to be performed and then forecast resources in terms of labor-hours, materials, and/or dollars. For example, a direct estimate could be quoted as "so many dollars." Many expert estimators can size up and estimate a job with just a little familiarization. One estimator I know can take a fairly complex drawing and, within just a few hours, develop a rough order-of-magnitude estimate of the resources required to build the item. Direct estimating is a skill borne of experience in both estimating and in actually performing the "hands-on" work.

70.11.3 Estimating by Analogy (Rules of Thumb)

This method is similar to the direct estimating method in that considerable judgment is required, but an additional feature is the comparison with some existing or past task of similar description. The estimator collects resource information on a similar or analogous task and compares the task to be estimated with the similar or analogous activity. The estimator would say that "this task should take about twice the time (man-hours, dollars, materials, etc.) as the one used as a reference." This judgmental factor (a factor of 2) would then be multiplied by the resources used for the reference task to develop the estimate for the new task. A significant pitfall in this method of estimating is the potential inability of the estimator to identify subtle differences in the two work activities and, hence, to be estimating the cost of a system based on one that is really not similar or analogous.

70.11.4 Firm Quotes

One of the best methods of estimating the resources required to complete a work element or to perform a work activity is the development of a firm quotation by the supplier or vendor. The two keys to the development of a realistic quotation are (1) the solicitation of bids from at least three sources, and (2) the development of a detailed and well-planned request for quotation. Years of experience by many organizations in the field of procurement have indicated that three bids are optimum from the standpoint of achieving the most realistic and reasonable price at a reasonable expenditure of effort. The solicitation of at least three bids provides sufficient check and balance and furnishes bid prices and conditions for comparison, evaluation, and selection. A good request for quotation (RFQ) is essential, however, to evaluate the bids effectively. The RFQ should contain ground rules, schedules, delivery locations and conditions, evaluation criteria, and specifications for the work. The RFQ should also state and specify the format required for cost information. A well-prepared RFQ will result in a quotation or proposal that will be easily evaluated, verified, and compared with independent estimates.

70.11.5 Handbook Estimating

Handbooks, catalogs, and reference books containing information on virtually every conceivable type of product, part, supplies, equipment, raw material, and finished material are available in libraries and bookstores and directly from publishers. Many of these handbooks provide labor estimates for installation or operation, as well as the purchase costs of the item. Some catalogs either do not provide price lists or provide price lists as a separate insert to permit periodic updates of prices without changing the basic catalog description. Information services provide microfilmed cassettes and on-line databases for access to the descriptions and costs of thousands and even tens of thousands of items.

If you produce a large number of estimates, it may pay to subscribe to a microfilm catalog and handbook data access system or, at least, to develop your own library of databases, handbooks, and catalogs.

70.11.6 The Learning Curve

The learning curve is a mathematical and graphical representation of the reduction in time, resources, or costs either actually or theoretically encountered in the conduct of a repetitive human activity. The theory behind the learning curve is that successive identical operations will take less time, use fewer resources, or cost less than preceding operations. The term *learning* is used because it relates primarily to the improvement of mental or manual skills observed when an operation is repeated, but *learning* can also be achieved by a shop or organization through the use of improved equipment, purchasing, production, or management techniques. When the learning curve is used in applications other than those involving the feedback loop that brings improvement of an individual's work activities, it is more properly named by one or more of the following terms:

Productivity improvement curve	Production improvement curve
Manufacturing progress function	Production acceleration curve
Experience curve	Time reduction curve
Progress curve	Cost improvement curve
Improvement curve	

Learning curve theory is based on the concept that as the total quantity of units produced doubles, the hours required to produce the last unit of this doubled quantity will be reduced by a constant percentage. This means that the hours required to produce unit 2 will be a certain percentage less than the hours required to produce unit 1; the hours required to produce unit 4 will be the same percentage less than the hours required to produce unit 2; the hours required to produce unit 8 will be the same percentage less than unit 4; and this constant percentage of reduction will continue for doubled quantities as long as uninterrupted production of the same item continues. The complement of this constant percentage of reduction is commonly referred to as the *slope.* This means that if the constant percentage of reduction is 10%, the slope would be 90%. Table 70.3 gives an example of a learning curve with 90% slope when the number of hours required to produce the first unit is 100.

Table 70.3 Learning Curve Values

Cumulative Units	Hours per Unit	Percent Reduction
1	100.00	
2	90.00	10
4	81.00	10
8	72.90	10
16	65.61	10
32	59.05	10

The reason for using the term *slope* in naming this reduction will be readily seen when the learning curve is plotted on coordinates with logarithmic scales on both the x and y axes (in this instance, the learning "curve" actually becomes a straight line). But first, let us plot the learning curve on conventional coordinates. You can see by the plot in Fig. 70.5 that it is truly a curve when plotted on conventional coordinates, and that the greater the production quantity, the smaller the incremental reduction in labor-hours required from unit to unit.

When the learning curve is plotted on log–log coordinates. as shown in Fig. 70.6, it becomes a straight line. The higher the slope, the flatter the line; the lower the slope, the steeper the line.

The effects of plotting curves on different slopes can be seen in Fig. 70.7, which shows the effects on labor-hour reductions of doubling the quantities produced 12 times. Formulas for the unit curve and the cumulative average curve are shown in Table 70.4.

Care should be taken in the use of the learning curve to avoid an overly optimistic (low) learning curve slope and to avoid using the curve for too few units in production. Most learning curve textbooks point out that this technique is credibly applicable only to operations that are done by hand (employ manual or physical operations) and that are highly repetitive.

70.11.7 Labor-Loading Methods

One of the most straightforward methods of estimating resources or labor-hours required to accomplish a task is the labor-loading or shop-loading method. This estimating technique is based on the fact that an experienced participant or manager of any activity can usually perceive, through judgment and knowledge of the activity being estimated, the number of individuals of various skills needed to accomplish a task. The shop-loading method is similar in that the estimator can usually predict what portion of an office or shop's capacity will be occupied by a given job. This percentage shop-loading factor can be used to compute labor-hours or resources if the total shop labor or total shop operation costs are known. Examples of the labor-loading and shop-loading methods based on 1896 labor-hours of on-the-job work per year are shown in Table 70.5.

70.11.8 Statistical and Parametric Estimating as Inputs to Detailed Estimating

Statistical and parametric estimating involves collecting and organizing historical information through mathematical techniques and relating this information to the work output that is being estimated. There are a number of methods that can be used to correlate historical cost and manpower information; the choice depends principally on mathematical skills, imagination, and access to data. These mathematical and statistical techniques provide some analytical relationship between the product, project, or service being estimated and its physical characteristics. The format most commonly used for statistical and parametric estimating is the *estimating relationship,* which relates some physical characteristic of the work output (weight, power requirements, size, or volume) with the cost or labor-hours required to produce it. The most widely used estimating relationship is linear. That is, the

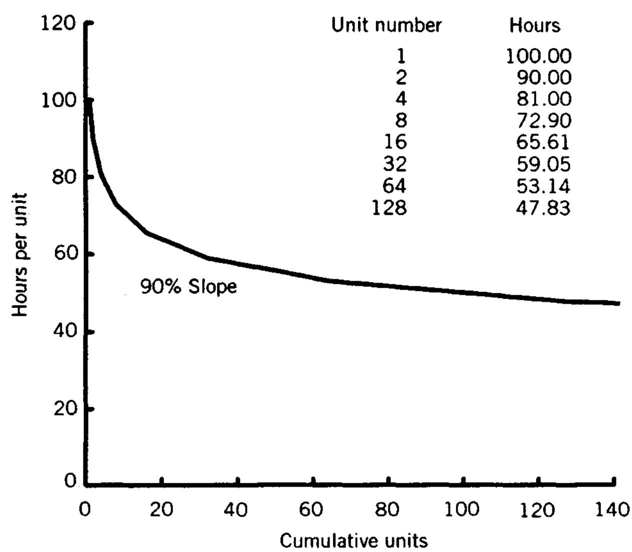

Fig. 70.5 Learning curve on a linear plot.

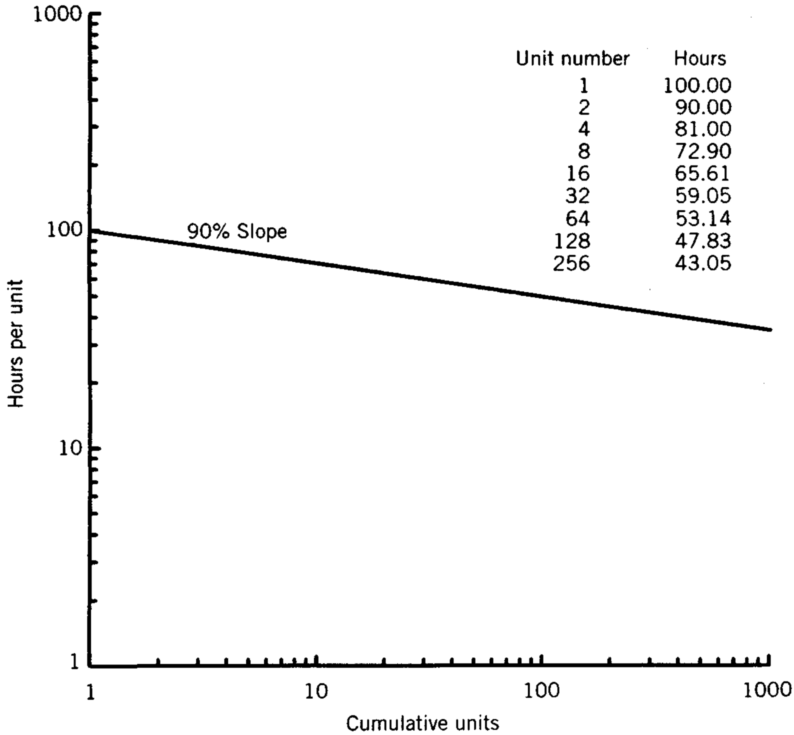

Fig. 70.6 Learning curve on a log–log plot.

mathematical equation representing the relationship is a linear equation, and the relationship can be depicted by a straight line when plotting on a graph with conventional linear coordinates for the x (horizontal) and y (vertical) axes. Other forms of estimating relationships can be derived based on curve-fitting techniques.

Estimating relationships have some advantages but certain distinct limitations. They have the advantage of providing a quick estimate even though very little is known about the work output except its physical characteristics. They correlate the present estimate with past history of resource utilization on similar items, and their use simplifies the estimating process. They require the use of statistical or mathematical skills rather than detailed estimating skills, which may be an advantage if detailed estimating skills are not available to the estimating organization.

On the other hand, because of their dependence on past (historical) data, they may erroneously indicate cost trends. Some products, such as mass-produced electronics, are providing more capability per pound, and lower costs per pound, volume, or component count every year. Basing electronics costs on past history may, therefore, result in noncompetitively high estimates. History should not be repeated if that history contains detrimental inefficiencies, duplications, unnecessary redundancies, rework, and overestimates. Often it is difficult to determine what part of historical data should be used to reflect future resource requirements accurately.

Finally, the parametric or statistical estimate, unless used at a very low level in the estimating process, does not provide in-depth visibility, and it does not permit determination of cost effects from subtle changes in schedule, performance, skill mix variations, or design requirements. The way to use the statistical or parametric estimate most effectively is to subdivide the work into the smallest possible elements and then to use statistical or parametric methods to derive the resources required for these small elements.

70.12 DEVELOPING A SCHEDULE

Schedule elements are time-related groupings of work activities that are placed in sequence to accomplish an overall desired objective. Schedule elements for a process can be represented by very small (minutes, hours, or days) time periods. The scheduling of a process is represented by the time the raw material or raw materials take during each step to travel through the process. The schedule for manufacturing a product or delivery of a service is, likewise, a time flow of the various components or actions into a completed item or activity.

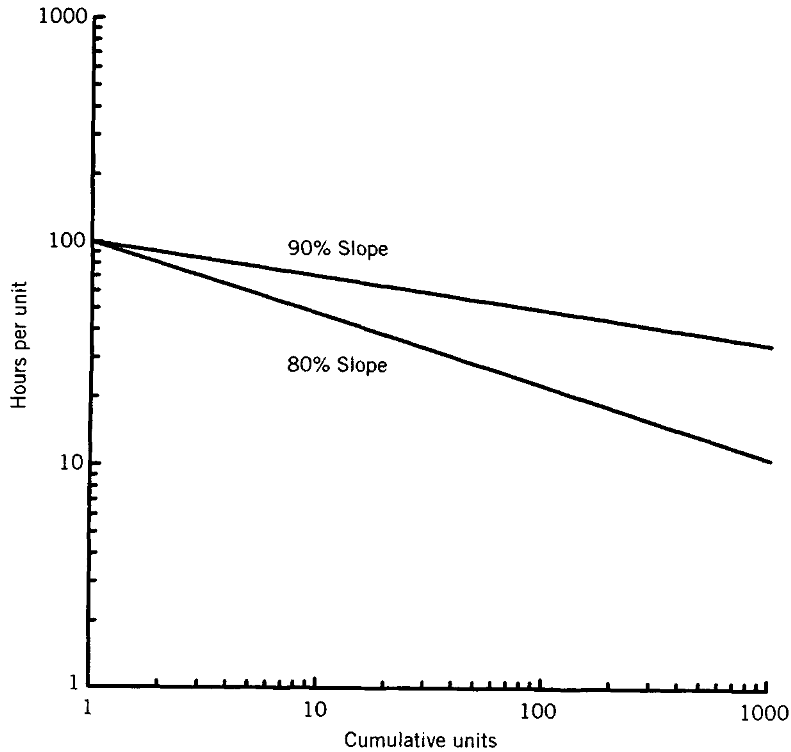

Fig. 70.7 Comparison between two learning curves.

A project (the construction or development of a fairly large, complex, or multidisciplinary tangible work output) contains distinct schedule elements called *milestones*. These milestones are encountered in one form or another in almost all projects:

1. Study and analysis
2. Design
3. Procurement of raw materials and purchased parts
4. Fabrication or manufacturing of components and subsystems
5. Assembly of the components and subsystems
6. Testing of the combined system to qualify the unit for operation in its intended environment
7. Acceptance testing, preparation, packaging, shipping, and delivery of the item
8. Operation of the item

Table 70.4 Learning Curve Formulas

Unit curve $Y_x = KX^N$

where Y_x = number of direct labor-hours required to produce the Xth unit
K = number of direct labor-hours required to produce the first unit
x = number of units produced
n = slope of curve expressed in positive hundredths (e.g., $n = 0.80$ for an 80% curve)

$$N = \frac{\log_{10} n}{\log_{10} 2}$$

Cumulative average curve

$$V_x \approx \frac{K}{X(1 + N)} [(x + 0.5)^{(1+N)} - (0.5)^{(1-N)}]$$

where V_x = the cumulative average number of direct labor-hours required to produce x units

Table 70.5 Labor-Loading and Shop-Loading Methods

	Time Increment (Year)						
	1	2	3	4	5	6	7
Labor-loading Method							
Engineers	1	1	1	2	1	0	0
Hours	1896	1896	1896	3792	1896	0	0
Technicians	3	4	4	6	2	1	0
Hours	5688	7584	7584	11,376	3792	1896	0
Draftsmen	0	0	1	3	6	4	2
Hours	0	0	1896	5688	11,376	7584	3792
Shop-loading Method							
Electrical shop (5 workers)	10%	15%	50%	50%	5%	0%	0%
Hours	948	1422	4740	4740	474	0	0
Mechanical shop (10 workers)	5%	5%	10%	80%	60%	10%	5%
Hours	948	948	1896	15,168	11,376	1896	948

70.13 TECHNIQUES USED IN SCHEDULE PLANNING

There are a number of analytical techniques used in developing an overall schedule of a work activity that help to ensure the correct allocation and sequencing of schedule elements: precedence and dependency networks, arrow diagrams, critical path bar charts, and program evaluation and review techniques (PERT). These techniques use graphical and mathematical methods to develop the best schedule based on sequencing in such a way that each activity is performed only when the required predecessor activities are accomplished.

70.14 ESTIMATING ENGINEERING ACTIVITIES

Engineering activities include the design, drafting, analysis, and redesign activities required to produce an end item. Costing of engineering activities is usually based on labor-loading and staffing resource estimates.

70.14.1 Engineering Skill Levels

The National Society of Professional Engineers has developed position descriptions and recommended annual salaries for nine levels of engineers. These skills levels are broad enough in description to cover a wide variety of engineering activities. The principal activities performed by engineers are described in the following paragraphs.

70.14.2 Design

The design activity for any enterprise includes conceptual design, preliminary design, final design, and design changes. The design engineer must design prototypes, components for development or preproduction testing, special test equipment used in development or preproduction testing, support equipment, and production hardware. Since design effort is highly dependent on the specific work output description, design hours must be estimated by a design professional experienced in the area being estimated.

70.14.3 Analysis

Analysis goes hand-in-hand with design and employs the same general skill level as design engineering. Categories of analysis that support, augment, or precede design are thermal, stress, failure, dynamics, manufacturing, safety, and maintainability. Analysis is estimated by professionals skilled in analytical techniques. Analysis usually includes computer time as well as labor-hours.

70.14.4 Drafting

Drafting, or engineering drawing, is one area in the engineering discipline where labor-hours can be correlated to a product: the completed engineering drawing. Labor-hour estimates must still be quoted in ranges, however, because the labor-hours required for an engineering drawing will vary considerably depending on the complexity of the item being drawn. The drafting times given in Table 70.6 are approximations for class-A drawings of nonelectronic (mechanical) parts where all the design information is available and where the numbers represent "board time," that is, actual time that the

Table 70.6 Engineering Draft Times

Drawing Letter Designation	Size	Approximate Board-Time Hours for Drafting of Class A Drawings (h)
A	8½ × 11	1–4
B	11 × 17	2–8
C	17 × 22	4–12
D	22 × 34	8–16
E and F	34 × 44 and 28 × 40	16–40
J	34 × 48 and larger	40–80

draftsman is working on the drawing. A class-A drawing is one that is fully dimensioned and has full supporting documentation. An additional eight hours per drawing is usually required to obtain approval and signoffs of stress, thermal, supervisors, and drawing release system personnel. If a "shop drawing" is all that is required (only sufficient information for manufacture of the part with some informal assistance from the designer and/or draftsman), the board time labor-hours required would be approximately 50% of that listed in Table 70.6.

70.15 MANUFACTURING/PRODUCTION ENGINEERING

The manufacturing/production engineering activity required to support a work activity is preproduction planning and operations analysis. This differs from the general type of production engineering wherein overall manufacturing techniques, facilities, and processes are developed. Excluded from this categorization is the design time of production engineers who redesign a prototype unit to conform to manufacturing or consumer requirements, as well as time for designing special tooling and special test equipment. A listing of some typical functions of manufacturing engineering follows:

1. Fabrication planning.
   a. Prepare operations sheets for each part.
   b. List operational sequence for materials, machines, and functions.
   c. Recommend standard and special tooling.
   d. Make up tool order for design and construction of special tooling.
   e. Develop standard time data for operations sheets.
   f. Conduct liaison with production and design engineers.
2. Assembly planning.
   a. Develop operations sheets for each part.
   b. Build first sample unit.
   c. Itemize assembly sequence and location of parts.
   d. Order design and construction of special jigs and fixtures.
   e. Develop exact component dimensions.
   f. Build any special manufacturing aids, such as wiring harness jig boards.
   g. Apply standard time data to operations sheet.
   h. Balance time cycles of final assembly line work stations.
   i. Effect liaison with production and design engineers.
   j. Set up material and layout of each work station in accordance with operations sheet.
   k. Instruct technicians in construction of the first unit.
3. Test planning.
   a. Determine overall test method to meet performance and acceptance specifications.
   b. Break total test effort into positions by function and desired time cycle.
   c. Prepare test equipment list and schematic for each position.
   d. Prepare test equipment design order for design and construction of special purpose test fixtures.
   e. Prepare a step-by-step procedure for each position.
   f. Effect liaison with production and design engineers.
   g. Set up test positions and check out.
   h. Instruct test operator on first unit.

Table 70.7 New Documentation

Function	Labor-Hours per Page
Research, liaison, technical writing, editing, and supervision	5.7
Typing and proofreading	0.6
Illustrations	4.3
Engineering	0.7
Coordination	0.2
Total[a]	11.5

[a]A range of 8 to 12 labor-hours per page can be used.

4. Sustaining manufacturing engineering.
   a. Debug, as required, engineering design data.
   b. Debug, as required, manufacturing methods and processes.
   c. Recommend more efficient manufacturing methods throughout the life of production.

The following statements may be helpful in deriving manufacturing engineering labor-hour estimates for high production rates:

1. Total fabrication and assembly labor-hours, divided by the number of units to be produced, multiplied by 20, gives manufacturing engineering start-up costs.
2. For sustaining manufacturing engineering, take the unit fabrication and assembly man-hours, multiply by 0.07. (These factors are suggested for quantities up to 100 units.)

70.15.1 Engineering Documentation

A large part of an engineer's time is spent in writing specifications, reports, manuals, handbooks, and engineering orders. The complexity of the engineering activity and the specific document requirements are important determining factors in estimating the engineering labor-hours required to prepare engineering documentation.

The hours required for engineering documentation (technical reports, specifications, and technical manuals) will vary considerably depending on the complexity of the work output; however, average labor-hours for origination and revision of engineering documentation have been derived based on experience, and these figures can be used as average labor-hours per page of documentation. (See Tables 70.7 and 70.8.)

70.16 ESTIMATING MANUFACTURING/PRODUCTION AND ASSEMBLY ACTIVITIES

A key to successful estimating of manufacturing activities is the process plan. A process plan is a listing of all operations that must be performed to manufacture a product or to complete a project, along with the labor-hours required to perform each operation. The process plan is usually prepared by an experienced foreman, engineer, or technician who knows the company's equipment, personnel, and capabilities, or by a process-planning department chartered to do all of the process estimating. The process planner envisions the equipment, work station, and environment; estimates the number

Table 70.8 Revised Documentation

Function	Labor-Hours per Page
Research, liaison, technical writing, editing, and supervision	4.00
Typing and proofreading	0.60
Illustrations	0.75
Engineering	0.60
Coordination	0.20
Total[a]	6.15

[a]A range of 4 to 8 labor-hours per page can be used.

of persons required; and estimates how long it will take to perform each step. From this information the labor-hours required are derived. Process steps are numbered, and space is left between operations listed to allow easy insertion of operations or activities as the process is modified.

A typical process plan for a welded cylinder assembly is given in Table 70.9. The process plan is used not only to plan and estimate a manufacturing or construction process, but often also as part of the manufacturing or construction work order itself. As such, it shows the shop or construction personnel each step to take in the completion of the work activity. Fabrication of items from metals, plastics, or other materials in a shop is usually called *manufacturing,* whereas fabrication of buildings, structures, bridges, dams, and public facilities on site is usually called *construction.* Different types of standards and estimating factors are used for each of these categories of work. Construction activities are covered in a subsequent chapter.

70.17 MANUFACTURING ACTIVITIES

Manufacturing activities are broken into various categories of effort, such as metal working and forming; welding, brazing, and soldering; application of fasteners; plating, printing, surface treating, heat treating; and manufacturing of electronic components (a special category). The most common method of estimating the time and cost required for manufacturing activities is the industrial engineering approach, whereby standards or target values are established for various operations. The term *standards* is used to indicate standard time data. All possible elements of work are measured, assigned a standard time for performance, and documented. When a particular job is to be estimated, all of the applicable standards for all related operations are added together to determine the total time.

The use of standards produces more accurate and more easily justifiable estimates. Standards also promote consistency between estimates as well as among estimators. Where standards are used, personal experience is desirable or beneficial, but not mandatory. Standards have been developed over a number of years through the use of time studies and synthesis of methods analysis. They are based on the level of efficiency that could be attained by a job shop producing up to 1000 units of any specific work output. Standards are actually synoptical values of more detailed times. They are adaptations, extracts, or benchmark time values for each type of operation. The loss of accuracy occasioned by summarization and/or averaging is acceptable when the total time for a system is being developed. If standard values are used with judgment and interpolations for varying stock sizes, reasonably accurate results can be obtained.

Machining operations make up a large part of the manufacturing costs of many products and projects. Machining operations are usually divided into setup times and run times. Setup time is the time required to establish and adjust the tooling, to set speeds and feeds on the metal-removal machine, and to program for the manufacture of one or more identical or similar parts. Run time is the time required to complete each part. It consists of certain fixed positioning times for each item being machined, as well as the actual metal-removal and cleanup time for each item. Values are listed for "soft" and "hard" materials. Soft values are for aluminum, magnesium, and plastics. Hard values are for stainless steel, tool steel, and beryllium. Between these two times would be standard values for brass, bronze, and medium steel.

70.18 IN-PROCESS INSPECTION

The amount of in-process inspection performed on any process, product, project, or service will depend on the cost of possible scrappage of the item as well as the degree of reliability required for the final work output. In high-rate production of relatively inexpensive items, it is often economically desirable to forgo in-process inspection entirely in favor of scrapping any parts that fail a simple go, no-go inspection at the end of the production line. On the other hand, expensive and sophisticated precision-manufactured parts may require nearly 100% inspection. A good rule of thumb is to add 10% of the manufacturing and assembly hours for in-process inspection. This in-process inspection does not include the in-process testing covered in the following paragraphs.

70.19 TESTING

Testing usually falls into three categories: (1) development testing, (2) qualification testing, and (3) production acceptance testing.

Rules of thumb are difficult to come by for estimating development testing, because testing varies with the complexity, uncertainty, and technological content of the work activity. The best way to estimate the cost of development testing is to produce a detailed test plan for the specific project and to cost each element of this test plan separately, being careful to consider all skills, facilities, equipment, and material needed in the development test program.

Qualification testing is required in most commercial products and on all military or space projects to demonstrate adequately that the article will operate or serve its intended purpose in environments far more severe than those intended for its actual use. Automobile crash tests are an example. Military products must often undergo severe and prolonged tests under high shock, thermal, and vibration loads as well as heat, humidity, cold, and salt spray environments. These tests must be meticulously planned and scheduled before a reasonable estimate of their costs can be generated.

Table 70.9 Process Plan

Operation Number	Labor-Hours	Description
010	—	Receive and inspect material (skins and forgings)
020	24	Roll form skin segments
030	60	Mask and chem-mill recessed pattern in skins
040	—	Inspect
050	36	Trim to design dimension and prepare in welding skin segments into cylinders (two)
060	16	Locate segments on automatic seam welder tooling fixture and weld per specification (longitudinal weld)
070	2	Remove from automatic welding fixture
080	18	Shave welds on inside diameter
090	16	Establish trim lines (surface plate)
100	18	Install in special fixture and trim to length
110	8	Remove from special fixture
120	56	Install center mandrel—center ring, forward and aft sections (cylinders)—forward and aft mandrel—forward and aft rings—and complete special feature setup
130	—	Inspect
140	24	Butt weld (4 places)
150	8	Remove from special feature and remove mandrels
160	59	Radiograph and dye penetrant inspect
170	—	Inspect dimensionally
180	6	Reinstall mandrels in preparation for final machining
190	14	Finish OD-aft
	10	Finish OD-center
	224	Finish OD-forward
200	40	Program for forward ring
220	30	Handwork (3 rings)
230	2	Reinstall cylinder assembly with mandrels still in place or on the special fixture
240	16	Clock and drill index holes
250	—	Inspect
260	8	Remove cylinder from special fixture—remove mandrel
270	1	Install in holding cradle
280	70	Locate drill jig on forward end and hand-drill leak check vein (drill and tap), and hand-drill hole pattern
290	64	Locate drill jig on aft ring and hand-drill hole pattern
300	—	Inspect forward and aft rings
310	8	Install protective covers on each end of cylinder
320	—	Transfer to surface treat
340	24	Remove covers and alodine
350	—	Inspect
360	8	Reinstall protective covers and return to assembly area

Table 70.10 Test Estimating Ratios

	Percent of Direct Labor		
	Simple	Average	Complex
Fabrication and Assembly Labor Base			
Receiving test	1	2	4
Production test	9	18	36
Total	10	20	40
Assembly Labor Base			
Receiving test	2	3	7
Production test	15	32	63
Total	17	35	70

Receiving inspection, production testing, and acceptance testing can be estimated using experience factors and ratios available from previous like-work activities. Receiving tests are tests performed on purchased components, parts, and/or subassemblies prior to acceptance by the receiving department. Production tests are tests of subassemblies, units, subsystems, and systems during and after assembly. Experience has shown, generally, that test labor varies directly with the amount of fabrication and assembly labor. The ratio of test labor to other production labor will depend on the complexity of the item being tested. Table 70.10 gives the test labor percentage of direct fabrication and assembly labor for simple, average, and complex items.

Special-purpose tooling and special-purpose test equipment are important items of cost because they are used only for a particular job; therefore, that job must bear the full cost of the tool or test fixture. In contrast to the special items, general-purpose tooling or test equipment is purchased as capital equipment, and costs are spread over many jobs. Estimates for tooling and test equipment are included in overall manufacturing start-up ratios shown in Table 70.11. Under "degree of precision and complexity," "high," means high-precision multidisciplinary systems, products, or subsystems; "medium" means moderately complex subsystems or components; and "low" means simple, straightforward designs of components or individual parts. Manual and computer-aided design hours required for test equipment are shown in Table 70.12 CAD drawings take approximately 67.5% of the time required (on the average) to produce manual drawings.

70.20 COMPUTER SOFTWARE COST ESTIMATING

Detailed cost estimates must include the cost of computer software development and testing where necessary to provide deliverable source code or to run the analysis or testing programs needed to develop products or services.

Because of the increasing number and types of computers and computer languages, it is difficult to generate overall ground rules or rules of thumb for computer software cost estimating. Productivity in computer programming is greatly affected by the skill and competence of the computer analyst or programmer. The advent of computer-aided software engineering (CASE) tools has dramatically

Table 70.11 Manufacturing Startup Ratios

Cost Element	Degree of Precision and Complexity	Recurring Manufacturing Costs Lot Quantity (%)			
		10	100	1000	10,000
Production planning	High	20	6	1.7	0.5
	Medium	10	3	0.8	0.25
	Low	5	1.5	0.4	0.12
Special tooling	High	10	6	3.5	2
	Medium	5	3	2	1
	Low	3	1.5	1	—
Special test equipment	High	10	6	3.5	2
	Medium	6	3	2	1
	Low	3	1.5	1	0.5
Composite total	High	40	18	8.7	4.5
	Medium	21	9	4.8	2.25
	Low	11	4.5	2.4	1.12

Table 70.12 Design Hours for Test Equipment

Type Design	Manual Hours/ Square Foot	Standard Drawing Size	Square Feet/ Drawing	Manual Hours/ Drawing	CAD Hours/ Drawing
Original concept	15	C	2.5	38	26
		D	5.0	75	51
		H	9.0	135	91
		J	11.0	165	111
Layout	10	B	1.0	10	7
		C	2.5	25	17
		D	5.0	50	34
		H	9.0	90	61
		J	11.0	110	74
Detail or copy	3	A	0.7	2.1	1.4
		B	1.0	3.0	2.0
		C	2.5	7.5	5.1
		D	5.0	15.0	10.1
		H	9.0	27.0	18.2
		J	11.0	33.0	22.3

accelerated the process of software analysis, development, testing, and documentation. Productivity is highly dependent on which CASE tools, if any, are utilized.

Complicated flight software for aircraft and space systems is subjected to design review and testing in simulations and on the actual flight computer hardware. A software critical design review is usually conducted about 43% of the way through the program; an integrated systems test is performed at the 67% completion mark; prototype testing is done at 80% completion; installation with the hardware is started with about 7% of the time remaining (at the 93% completion point).

70.21 LABOR ALLOWANCES

"Standard times" assume that the workers are well trained and experienced in their jobs, that they apply themselves to the job 100% of the time, that they never make a mistake, take a break, lose efficiency, or deviate from the task for any reason. This, of course, is an unreasonable assumption because there are legitimate and numerous unplanned work interruptions that occur with regularity in any work activity. Therefore, labor allowances must be added to any estimate that is made up of an accumulation of standard times. These labor allowances can accumulate to a factor of 1.5 to 2.5. The total standard time for a given work activity, depending on the overall inherent efficiency of the shop, equipment, and personnel, will depend on the nature of the task. Labor allowances are made up of a number of factors that are described in the following sections.

70.21.1 Variance from Measured Labor-Hours

Standard hours vary from actual measured labor-hours because workers often deviate from the standard method or technique used or planned for a given operation. This deviation can be caused by a number of factors ranging from the training, motivation, or disposition of the operator to the use of faulty tools, fixtures, or machines. Sometimes shortages of materials or lack of adequate supervision are causes of deviations from standard values. These variances can add 5 to 20% to standard time values.

70.21.2 Personal, Fatigue, and Delay (PFD) Time

Personal times are for personal activities such as coffee breaks, trips to the restroom or water fountain, unforeseen interruptions, or emergency telephone calls. Fatigue time is allocated because of the inability of a worker to produce at the same pace all day. Operator efficiency decreases as the job time increases. Delays include unavoidable delays caused by the need for obtaining supervisory instructions, equipment breakdown, power outages, or operator illness. PFD time can add 10 to 20% to standard time values.

70.21.3 Tooling and Equipment Maintenance

Although normal or routine equipment maintenance can be done during times other than operating shifts, there is usually some operator-performed machine maintenance activity that must be performed during the machine duty cycle. These activities include adjusting tools, sharpening tools, and periodically cleaning and oiling machines. In electroplating and processing operations, the operator maintains solutions and compounds, and handles and maintains racks and fixtures. Tooling and equipment maintenance can account for 5 to 12% of standard time values.

70.21.4 Normal Rework and Repair

The overall direct labor-hours derived from the application of the preceding three allowance factors to standard times must be increased by additional amounts to account for normal rework and repair. Labor values must be allocated for rework of defective purchased materials, rework of in-process rejects, final test rejects, and addition of minor engineering changes. Units damaged on receipt or during handling must also be repaired. This factor can add 10 to 20% direct labor-hours to those previously estimated.

70.21.5 Engineering Change Allowance

For projects where design stability is poor, where production is initiated prior to final design release, and where field testing is being performed concurrently with production, an engineering change allowance should be added of up to 10% of direct labor-hours. Change allowances vary widely for different types of work activities. Even fairly well defined projects, however, should contain a change allowance.

70.21.6 Engineering Prototype Allowance

The labor-hours required to produce an engineering prototype are greater than those required to produce the first production model. Reworks are more frequent, and work is performed from sketches or unreleased drawings rather than from production drawings. An increase over first production unit labor of 15 to 25% should be included for each engineering prototype.

70.21.7 Design Growth Allowance

Where estimates are based on incomplete drawings, or where concepts or early breadboards only are available prior to the development of a cost estimate, a design growth allowance is added to all other direct labor costs. This design growth allowance is calculated by subtracting the percentage of design completion from 100%, as shown in the following tabulation:

Desirable Design Completion (%)	Design Completed (%)	Design Growth Allowance (%)
100	50	50
100	75	25
100	80	20
100	90	10
100	100	0

70.21.8 Cost Growth Allowance

Occasionally a cost estimate will warrant the addition of allowances for cost growth. Cost growth allowances are best added at the lowest level of a cost estimate rather than at the top levels. These allowances include reserves for possible misfortunes, natural disasters, strikes, and other unforeseen circumstances. Reserves should not be used to account for normal design growth. Care should be taken in using reserves in a cost estimate because they are usually the first cost elements that come under attack for removal from the cost estimate or budget. Remember, cost growth with an incomplete design is a certainty, not a reserve or contingency! Defend your cost growth allowance, but be prepared to relinquish your reserve if necessary.

70.22 ESTIMATING SUPERVISION, DIRECT MANAGEMENT, AND OTHER DIRECT CHARGES

Direct supervision costs will vary with the task and company organization. Management studies have shown that the span of control of a supervisor over a complex activity should not exceed 12 workers. For simple activities, the ratio of supervisors to employees can go down. But the 1:12 ratio (8.3%) will usually yield best results. Project management for a complex project can add an additional 10 to 14%. Other direct charges are those attributable to the project being accomplished but not included in direct labor or direct materials. Transportation, training, and reproduction costs, as well as special service or support contracts and consultants, are included in the category of "other direct costs."

Two cost elements of "other direct costs" that are becoming increasingly prominent are travel and transportation costs. A frequent check on public and private conveyance rates and costs is mandatory. Most companies provide a private vehicle mileage allowance for employees who use their own vehicles in the conduct of company business. Rates differ and depend on whether the private conveyance is being utilized principally for the benefit of the company or principally for the convenience of the traveler. Regardless of which rate is used, the mileage allowance must be periodically updated to keep pace with actual costs. Many companies purchase or lease vehicles to be used by their employees on official business.

Per diem travel allowances or reimbursement for lodging, meals, and miscellaneous expenses must also be included in overall travel budgets. These reimbursable expenses include costs of a motel or hotel room; food, tips, and taxes; local transportation and communication; and other costs such as laundry, mailing costs, and on-site clerical services. Transportation costs include the transport of equipment, supplies, and products, as well as personnel, and can include packaging, handling, shipping, postage, and insurance charges.

70.23 THE USE OF "FACTORS" IN DETAILED ESTIMATING

The practice of using factors is becoming increasingly common, particularly in high-technology work activities and work outputs. One company uses an "allocation factor," which allocates miscellaneous labor-oriented functions to specific functions such as fabrication or assembly. This company adds 14.4% to fabrication hours and 4.1% to assembly hours to cover miscellaneous labor-hour expenditures associated with these two functions. It is also common to estimate hours for planning, tooling, quality and inspection, production support, and sustaining engineering based on percentages of manufacturing and/or assembly hours. Tooling materials and computer supplies are sometimes estimated based on so much cost per tooling hour, and miscellaneous shop hardware (units, bolts, fasteners, cleaning supplies, etc.), otherwise known as *pan stock,* is estimated at a cost per manufacturing hour.

The disadvantage of the use of such factors is that inefficiencies can become embedded in the factored allowances and eventually cause cost growth. A much better method of estimating the labor-hours and materials required to accomplish these other direct activities is to determine the specific tasks and materials required to perform the job by laborloading, shoploading, or process-planning methods. When the materials, labor-hours, and other direct costs have been estimated, the basic direct resources required to do the job have been identified. The estimator can now move into the final steps of the detailed estimating process with the full assurance that all work elements and all cost elements have been included in the detailed estimate.

70.24 CONCLUDING REMARKS

In summary, detailed cost estimating involves meticulous penetration into the smallest feasible portions of a work output or work activity and the systematic and methodical assembly of the resources in all cost, work, and schedule elements. Detailed estimating requires detailed design, manufacturing, and test descriptions, and involves great time, effort, and penetration into the resources required to do the job. Wherever possible, detailed estimates should be used to establish a firm and credible cost estimate and to verify and substantiate higher-level parametric estimates.