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COST EVALUATION

16.1
INTRODUCTION

An engineering design is not complete until we have a good idea of the cost required to build the design or manufacture the product. Generally, among functionally equivalent alternatives, the lowest-cost design will be successful in a free marketplace. The fact that we have placed this chapter on cost evaluation toward the end of the text does not reflect the importance of the subject.

Understanding the elements that make up cost is vital because competition between companies and between nations is fiercer than ever. The world is becoming a single gigantic marketplace in which newly developing countries with very low labor costs are acquiring technology and competing successfully with the well-established industrialized nations. Maintaining markets requires a detailed knowledge of costs and an understanding of how new technology can lower costs.

Decisions made in the design process commit 70 to 80 percent of the cost of a product. It is in the conceptual and embodiment design stages that a majority of the costs are locked into the product. Thus, this chapter emphasizes how accurate cost estimates can be made early in the design process.

Cost estimates are used in the following ways:

1. To provide information to establish the selling price of a product or a quotation for a good or service.
2. To determine the most economical method, process, or material for manufacturing a product.
3. To become a basis for a cost-reduction program.
4. To determine standards of production performance that may be used to control costs.
5. To provide input concerning the profitability of a new product.

It can be appreciated that cost evaluation inevitably becomes a very detailed and "nitty-gritty" activity. Detailed information on cost analysis rarely is published in the technical literature, partly because it does not make interesting reading but more important, because cost data are highly proprietary. Therefore, the emphasis in this chapter will be on the identification of the elements of costs and on some of the more generally accepted cost evaluation methods. Cost estimation within a particular industrial or governmental organization will follow highly specialized and standardized procedures particular to the organization. However, the general concepts of cost evaluation described here will still be valid.

16.2 CATEGORIES OF COSTS

We can divide all costs into two broad categories: product costs and period costs. *Product costs* are those costs that vary with each unit of product made. Material cost and labor cost are good examples. *Period costs* derive their name from the fact that they occur over a period of time regardless of the amount (volume) of product that is made or sold. An example would be the insurance on the factory equipment or the expenses associated with selling the product. Another name for a product cost is *variable cost*, because the cost varies with the volume of product made. Another name for period cost is *fixed cost*, because the costs remain the same regardless of the volume of product made. Fixed costs cannot be readily allocated to any particular product or service that is produced.

Yet another way of categorizing costs is by direct cost and indirect cost. A *direct cost* is one that can be directly associated with a particular unit of product that is manufactured. In most cases, a direct cost is also a variable cost, like materials cost. Advertising for a product would be a direct cost when it is assignable to a specific product or product line, but it is not a variable cost because the cost does not vary with the quantity produced. An *indirect cost* cannot be identified with any particular product. Examples are rent on the factory building, cost of utilities, or wages of the shop floor supervisors. Often the line between direct costs and indirect costs is fuzzy. For example, equipment maintenance would be considered a direct cost if the machines are used exclusively for a single product line, but if many products were manufactured with the equipment, their maintenance would be considered an indirect cost.

Returning to the cost classifications of fixed and variable costs, examples are:

Fixed costs

1. Indirect plant cost
   (*a*) Investment costs
      Depreciation on capital investment
      Interest on capital investment and inventory
      Property taxes
      Insurance
   (*b*) Overhead costs (burden)
      Technical services (engineering)
      Product design and development

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Nontechnical services (office personnel, security, etc.)
General supplies
Rental of equipment

2. Management and administrative expenses
   (*a*) Share of cost of corporate executive staff
   (*b*) Legal staff
   (*c*) Share of corporate research and development staff
   (*d*) Marketing staff
3. Selling expenses
   (*a*) Sales force
   (*b*) Delivery and warehouse costs
   (*c*) Technical service staff

Variable costs

1. Materials
2. Direct labor (including fringe benefits)
3. Direct production supervision
4. Maintenance costs
5. Power and utilities
6. Quality-control staff
7. Royalty payments
8. Packaging and storage costs
9. Scrap losses and spoilage

Fixed costs such as marketing and sales costs, legal expense, security costs, financial staff expense, and administrative costs are often lumped into an overall category known as *general and administrative expenses* (G&A expenses). The preceding list of fixed and variable costs is meant to be illustrative of the chief categories of costs, but it is not exhaustive.

The way the elements of cost build up to establish a selling price is shown in Fig. 16.1. The chief cost elements of direct material, direct labor, and any other direct expenses determine the *prime cost.* To it must be added indirect manufacturing costs such as light, power, maintenance, supplies, and factory indirect labor. This is the *factory cost.* The *manufacturing cost* is made up of the factory cost plus general fixed expenses such as depreciation, engineering, taxes, office staff, and purchasing. The *total cost* is the manufacturing cost plus the sales expense. Finally, the *selling price* is established by adding a profit to the total cost.

Another important cost category is *working capital,* the funds that must be provided in addition to fixed capital and land investment to get a project started and provide for subsequent obligations as they come due. It consists of raw material on hand, semifinished product in the process of manufacture, finished product in inventory, accounts receivable,[1] and cash needed for day-to-day operation. The working capital

1. Accounts receivable represents products that have been sold but for which your company has not yet been paid.

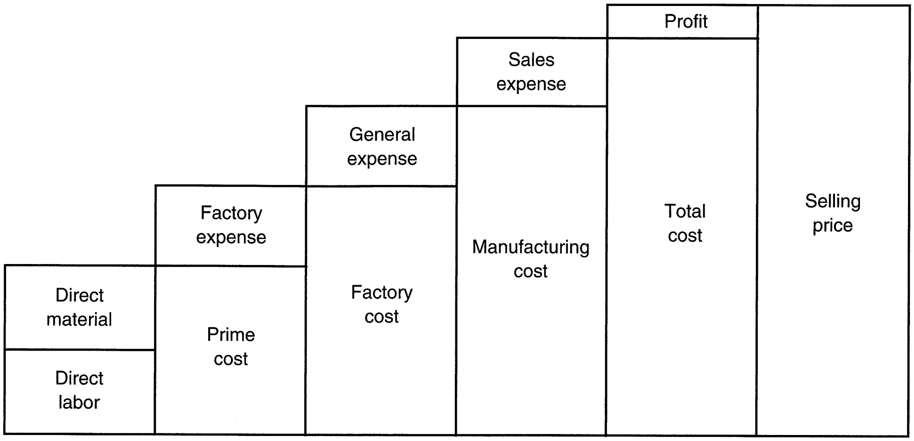

FIGURE 16.1
Elements of cost that establish the selling price.

is tied up during the life of the plant, but it is considered to be fully recoverable at the end of the life of the project.

Break-Even Point

Separating costs into fixed and variable costs leads to the concept of the break-even point (BEP), Fig. 16.2. The break-even point is the sales or production volume at which sales and costs balance. Operating beyond the BEP results in profits; operating below the BEP results in losses. Let P be the unit sales price ($/unit), v be the variable cost ($/unit), and f be the fixed cost ($). Q is the number of production units, or the sales volume of products sold. The gross profit Z is given by[2]

$$Z = PQ - (Qv + f)$$

At the break-even point, $Q = Q_{BEP}$ and $Z = 0$

$$Q_{BEP}(P - v) = f \quad \text{Therefore, } Q_{BEP} = \frac{f}{P - v} \tag{16.1}$$

EXAMPLE 16.1 A new product has the following cost structure over one month of operation. Determine the break-even point.

Labor cost 2.50 $/unit	Material cost 6.00 $/unit
G & A expenses $1200	Depreciation on equipment $5000
Factory expenses $900	Sales & distribution overhead $1000
Profit $1.70 $/unit	

Total variable cost, v, = 2.50 + 6.00 = 8.50 $/unit

2. Gross profit is the profit before subtracting general and administrative expenses and taxes.

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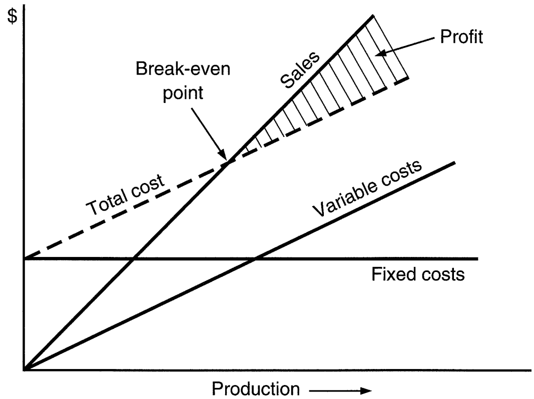

FIGURE 16.2
Break-even curve showing relation between fixed and variable costs and profit before taxes.

Total fixed cost, f, = 1200 = 5000 + 800 + 1000 = \$8000

Sales price, P = 8.50 + 1.70 = \$10.20

$$Q_{BEP} = \frac{f}{P - v} = \frac{8000}{10.20 - 8.50} = 4706\,\text{units}$$

What sales price would be needed for the product to break even at 1000 units?

$$P = \frac{f + Q_{BEP}v}{Q_{BEP}} = \frac{8000 + 1000(8.50)}{1000} = \frac{16{,}500}{1000} = 16.50\,\$/\text{units}$$

Elements of Manufacturing Costs of a Product

The categories of manufacturing cost shown in Fig. 16.1 can be broken down further into three broad categories: (1) component costs, (2) assembly costs, and (3) overhead.

Component (part) costs can be divided into two categories: cost of *custom parts* made according to the company's design from semifinished materials like bar stock, sheet metal, or plastic pellets, and cost of *standard parts* that are purchased from suppliers. Custom parts are made in the company's own plants or outsourced to suppliers. Standard parts comprise standard components like bearings, motors, electronic chips, and screws, but they also include OEM subassemblies (parts made by suppliers for original equipment manufacturers) like diesel engines for trucks and seats and instrument panels for automobiles. No matter the origin of its manufacture, the cost of making a part includes the material cost, the cost of labor and machine time, the cost of tooling, and the cost of tool changing and setup. For outsourced parts, these costs are in the purchase price of the part along with a modest profit for the supplier.

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The cost for manufacturing a product consists of (1) the costs of the parts, as defined by the bill of materials for the product, (2) the cost for assembling the parts into the product, and (3) overhead costs. Assembly generally requires labor costs for assembly, and often special fixtures and other equipment. Overhead is the cost category that accounts for those costs of manufacture that cannot be directly attributed to each unit of production. This is discussed in Sec. 16.3.

Selling Price

Manufacturing cost is an important cost element in establishing the selling price of a product. Two other cost components that must be considered in reaching the final cost of a product are preparing the product for shipping, and shipping it to a distribution point. The selling price, which is usually the price paid by wholesalers, is the sum of these costs plus the manufacturing cost plus the profit to the manufacturer.

$$\text{Profit} = \text{Selling price} - \text{Total cost of product realization} \tag{16.2}$$

The profit percentage (margin) is determined by the acceptance and competition in the marketplace for the product. For unique products it may be 40 to 60 percent, but 10 to 30 percent is a more typical value. A well-accepted business principle is that for a new business venture, the expected return must exceed the cost of the investment that must be made. This leads to the following simplified markup pricing model.[3]

$$\text{Unit price} = \frac{\left(\dfrac{iI}{N_y} + \mathrm{f} + \mathrm{v}N\right)}{N} \tag{16.3}$$

where i = expected return on investment (decimal), I = capital investment (dollars),
N_y = payback period for investment (years), f = fixed cost for product (dollars),
v = variable cost (dollars per unit), N = number of units sold

Wholesalers sell the product to retail outlets. The markup over wholesale cost will depend on the nature of the market in which the product sells. If it is a tightly controlled market, then the markup can be as great as 100 percent; if it is a highly competitive market with many "big box" stores competing with each other, then it may only be 20 percent.

16.3 OVERHEAD COST

Perhaps no aspect of cost evaluation creates more confusion and frustration in the young engineer than overhead cost. Many engineers consider overhead to be a tax on their creativity and efforts, rather than the necessary and legitimate cost it is. Overhead can be computed in a variety of ways. Therefore, you should know something about how accountants assign overhead charges.

An overhead cost[4] is any cost not specifically or directly associated with the production of identifiable goods or services. The two main categories of overhead costs are factory or plant overhead and corporate overhead. *Factory overhead* includes the

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3. P.F. Ostwald and T.S. McLaren, *Cost Analysis and Estimating for Engineering and Management,* p. 381, Pearson Prentice Hall, Upper Saddle River, NJ, 2004.

4. The term "overhead" arose in early 20th century factories where the bosses were generally located in second-floor offices over the factory floor.

costs of manufacturing that are not related to a particular product. *Corporate overhead* is based on the costs of running the company that are outside the manufacturing or production activities. Since many manufacturing companies operate more than one plant, it is important to be able to determine factory overhead for each plant and to lump the other overhead costs into corporate overhead. Typical cost contributions to corporate overhead are the salaries and fringe benefits of corporate executives, sales personnel, accounting and finance, legal staff, R&D, corporate engineering and design staff, and the operation of the corporate headquarters building.

One overhead rate may be assigned to an entire factory, but it is more common to designate different overhead rates to departments or cost centers. How the overhead is to be distributed is a management decision that is implemented by accountants.

$$\text{Overhead rate} = \text{OH} = \frac{\text{Overhead charges}}{\text{Basis}} \tag{16.4}$$

Historically, the most common basis for allocating overhead charges is direct labor dollars or hours. This was chosen in the beginning of cost accounting because most manufacturing was highly labor intensive, and labor represented the major fraction of the total cost. Other bases for distributing overhead charges are machine hours, materials cost, number of employees, and floor space.

EXAMPLE 16.2 A modest-sized corporation operates three plants with direct labor and factory overhead as follows:

Cost	Plant A	Plant B	Plant C	Total
Direct labor	\$750,000	400,000	500,000	1,650,000
Factory overhead	900,000	600,000	850,000	2,350,000
Total	1,650,000	1,000,000	1,350,000	4,000,000

In addition, the cost of management, engineering, sales, accounting, etc., is \$1,900,000. Find the corporate overhead rate based on direct labor.

$$\text{Corporate overhead rate} = \frac{1{,}900{,}000}{1{,}650{,}000} = 1.15 = 115\%$$

Then, the allocation of corporate overhead to Plant A would be \$750,000(1.15) = \$862,500

In the next example of overhead costs, we consider the use of factory overhead in determining the cost of performing a manufacturing operation.

EXAMPLE 16.3 A batch of 100 parts requires 0.75 h of direct labor each in the gear-cutting operation. If the cost of direct labor is \$20 per h and the factory overhead is 160 percent, determine the total cost of processing a batch.

The cost of processing a batch is: $(100\text{ parts})(0.75\text{ h/parts})(\$20.00/\text{h}) = \$1500$

The factory overhead charge is: $\$1500(1.60) = \$2400$

The cost of gear cutting for a batch of 100 parts is processing cost + overhead charge = $\$1500 + 2400 = \$3900$. The unit cost is \$39.00.

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The overhead rate for a particular cost center or remanufacturing process is often expressed in dollars per direct labor hour ($/DLH). In Example 16.3, this is $2400/(100 × 0.75) = 32$/DLH. The allocation of overhead on the basis of DLH sometimes can cause confusion as to the real cost when process improvement results in an increase in manufacturing productivity.

EXAMPLE 16.4 A change from a high-speed steel-cutting tool to a new coated WC tool results in halving the time for a machining operation because the new carbide tool can cut at a much faster speed without "losing its edge." The data for the old tool and the new tool are shown in columns 1 and 2 of the following table. Because the cost of overhead is based on DLH, the cost of overhead apparently is reduced along with the cost of direct labor. The apparent savings per piece is 200 – 100 = $100. However, a little reflection will show that the cost elements that make up the overhead (supervision, tool room, maintenance, etc.) will not change because the DLH is reduced. Since the overhead is expressed as $/DLH, the overhead will actually double if DLH is halved. This true cost is reflected in column (3). Thus, the actual savings per piece is 200 – 160 = $40.

	(1) Old Tool	(2) New Tool (Apparent Cost)	(3) New Tool (True Cost)
Machining time, DLH	$4	$2	$2
Direct labor rate, $/h	$20	$20	$20
Direct labor cost	$80	$40	$40
Overhead rate, $/DLH	$30	$30	$60
Cost of overhead	$120	$60	$120
Cost of direct labor and overhead	$200	$100	$160

In many manufacturing situations, overhead allocation based on something other than DLH may be appropriate. Consider a plant whose major cost centers are a machine shop, a paint line, and an assembly department. We see that it is reasonable for each cost center to have a different overhead rate in units appropriate to the function that is performed.

Cost center	Est. Factory Overhead	Est. Number of Units	Overhead Rate
Machine shop	$250,000	40,000 machine hours	$6.25 per machine hour
Paint line	80,000	15,000 gal of paint	$5.33 per gallon of paint
Assembly dept.	60,000	10,000 DLH	$6.00 per DLH

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The preceding examples show that the allocation of overhead on the basis of DLH may not be the best way to do it. This is particularly true of automated production systems where overhead has become the dominant manufacturing cost. In such situations, overhead rates are often between 500 and 800 percent of the direct labor cost. In the limit, the overhead rate for an unmanned manufacturing operation would be infinity.

An advance on using DLH to determine overhead distribution is to use the *productive hour cost rate.*[5] It is applied where overhead is being applied to cost centers, each consisting of common types of machines. Typically the factory will have a budgeted amount, based on past experience, for each indirect cost category. Typical categories, along with the basis for allocation, are: depreciation (MACRS value), space (sq. ft), indirect labor (DLH), utilities (HP hr), and engineering services (DLH). For example, the indirect labor pool is spread to the cost centers in proportion to each center's fraction of the DLH multiplied by the total factory dollar budget for indirect labor. Each other category is determined in the same way, but using its appropriate allocation basis. With overhead allocated among cost centers, the *machine hour cost rate* is found for each center by dividing its overhead by the budgeted hours. This is the overhead rate for work done in the cost center. Then the *productive hour cost rate* is the sum of the machine hour cost rate and the hourly wage rate (including benefits).

The productive hour cost rate provides an accurate method of allocating overhead costs when the use of production equipment plays a major role in the cost analysis. It is flexible enough to make allowance for the use of highly automated equipment. In this case, there would be a very low charge for hourly wages. If one of the cost centers was an assembly area where hand assembly was being done, the depreciation and tooling charges would be negligible, while hourly wages would be significant.

16.4
ACTIVITY-BASED COSTING

In a traditional cost accounting system, indirect costs are assigned to products using direct labor hours or some other unit-based measure to determine overhead cost. We have already seen (Example 16.4) where traditional cost accounting does not accurately represent cost when a large productivity gain has been made. Other types of distortion caused by the cost accounting system are concerned with timing; for example, the R&D costs of future products are charged to products currently being produced, and more complex products will require support costs in greater proportion to their production volume. For these and other reasons a new way of assigning indirect costs called *activity-based costing* (ABC) has been developed.[6]

Rather than assigning costs to an arbitrary reference like direct labor hours or machine hours, ABC recognizes that products incur costs by the *activities* that are required for their design, manufacture, sale, delivery, and service. In turn, these activities create cost by consuming support services such as engineering design, production planning, machine setup, and product packing and shipping. To implement an ABC system you must identify the major activities undertaken by the support departments and identify a *cost driver* for each. Typical cost drivers might be hours of engineering design, hours of testing, number of orders shipped, or number of purchase orders written.

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5. P.F. Ostwald and T.S. McLaren, op. cit., pp. 160–63.
6. R.S. Kaplan and R.E. Cooper, *Cost and Effect: Using Integrated Cost Systems to Drive Profitability and Performance,* Harvard Business School Press, Boston, MA, 1998.

EXAMPLE 16.5 A company assembles electronic components for specialized test equipment. Two products A75 and B20 require 8 and 10.5 min, respectively, of direct labor, which costs \$16 per hour. Product A75 consumes \$35.24 of direct materials and product B20 consumes \$51.20 of direct materials.

Using a traditional cost accouting system where all overhead costs are allocated to direct labor hours at a rate of \$230 per DLH, the cost of a product would be:

Direct labor cost + direct material cost + overhead cost

$$\text{For product A75: } \$16(8/60) + \$35.24 + 230(8/60) = 2.13 + 35.24 + 30.59 = \$67.96$$

$$\text{For product B20: } \$16(10.5/60) + \$51.20 + \$230(10./60) = 2.80 + 51.20 + 40.25 = \$94.25$$

In an attempt to get a more accurate estimate of costs, the company turns to the ABC approach. Six cost drivers are identified for this manufacturing system.[7]

Activity	Cost Driver	Rate
Engineering	Hours of engineering services	\$60.00 per hour
Production setup	Number of setups	\$100.00 per setup
Materials handling	Number of components	\$0.15 per component
Automated assembly	Number of components	\$0.50 per component
Inspection	Hours of testing	\$40.00 per hour
Packing and shipping	Number of orders	\$2.00 per order

The level of activity of each cost driver must be obtained from cost records.

	Product A75	Product B20
Number of components	36	12
Hours of engineering services	0.10	0.05
Production batch size	50	200
Hours of testing	0.05	0.02
Units per order	2	25

In building the cost comparison between products we start with direct labor and direct material costs, as given above. Then we turn to ABC in allocating the overhead costs. We apply the activity level of the cost drivers to the cost rate of the driver. For example, for Product A75,

$$\text{Engineering services: } 0.10 \text{ h/unit} \times \$60/\text{h} = \$6.00/\text{unit}$$

$$\text{Production setups: } 100\frac{\$}{setup}\frac{1}{50}\frac{setup}{unit} = 2.00\frac{\$}{unit}$$

$$\text{Materials handling: } 36\frac{components}{unit} \times 0.15\frac{\$}{component} = 5.40\frac{\$}{unit}$$

$$\text{Packing and shipping: } 2.00\frac{\$}{order}\frac{1}{2}\frac{order}{units} = 1.00\frac{\$}{unit}$$

7. In a real ABC study there would be many more activities and cost drivers than are used in this example.

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Comparison of the Two Products on Activity-Based Costing

	A75	B20
Direct labor	2.13	2.80
Direct materials	35.24	51.20
Engineering	6.00	3.00
Production setups	2.00	0.50
Materials handling	5.40	1.80
Assembly	18.00	6.00
Testing	2.00	0.80
Packing and shipping	1.00	0.80
	$71.77	$66.90

We see that by using ABC, we find that product B20 is less costly to produce. This shift has come entirely from changing the allocation of overhead costs from DLH to cost drivers based on the main activities in producing the product. B20 incurs lower overhead charges chiefly because it is a less complex product using fewer components and requiring less support for engineering, materials handling, assembly, and testing.

Using ABC leads to improved product-based decisions through more accurate cost data. This is especially important when manufacturing overhead accounts for a large fraction of manufacturing costs. By linking financial costs with activities, ABC provides cost information to complement nonfinancial indicators of performance like quality. The preceding data clearly show the need to reduce the number of components to lower the cost of materials handling and assembly. On the other hand, using only a single cost driver to represent an activity can be too simple. More complex factors can be developed, but at a considerable cost in the complexity of the ABC system.

ABC cost accounting is best used when there is diversity in the product mix of a company in terms of such factors as complexity, different maturity of products, production volume or batch sizes, and need for technical support. Computer-integrated manufacturing is a good example of a place where ABC can be applied because it has such high needs for technical support and such low direct labor costs.

There is more work in using ABC than traditional cost accounting, but this is partly compensated by the use of computer technology to accumulate the cost data. A big advantage of ABC is that when the system is in place it points to those areas of indirect cost where large savings could be made. Thus, ABC is an important component of a total quality management program aimed at process improvement and cost reduction.

16.5 METHODS OF DEVELOPING COST ESTIMATES

The methods to develop cost evaluations fall into three categories: (1) analogy, (2) parametric and factor methods, and (3) methods engineering.

16.5.1 Analogy

In cost estimation by analogy, the future costs of a project or design are based on past costs of a similar project or design, with due allowance for cost escalation and technical differences. The method therefore requires a database of experience or published cost data. This method of cost evaluation commonly is used for feasibility studies of chemical plants and process equipment.[8] When cost evaluation by analogy is used, future costs must be based on the same state of the art. For example, it would be valid to use cost data on a 777 jet transport aircraft to estimate costs for a larger 777, but it would not be correct to use the same data to predict the cost of the Boeing 787 because the main structures have changed from riveted aluminum construction to autoclave-bonded polymer-graphite fiber construction.

A concern with determining cost by analogy is to be sure that costs are being evaluated on the same basis. Equipment costs often are quoted FOB (free on board) the manufacturer's plant location, so delivery cost must be added to the cost estimate. Costs sometimes are given for the equipment not only delivered to the plant site but also installed in place, although it is more usual for costs to be given FOB some shipping point.

16.5.2 Parametric and Factor Methods

In the *parametric* or statistical approach to cost estimation, techniques such as regression analysis are used to establish relations between system cost and key parameters of the system, such as weight, speed, and power. This approach involves cost estimation at a high level of aggregation, so it is most helpful in the problem definition stage of conceptual design. For example, the cost of developing a turbofan aircraft engine might be given by

$$C = 0.13937 x_1^{0.7435} x_2^{0.0775}$$

where C is in millions of dollars, x_1 is maximum engine thrust, in pounds, and x_2 is the number of engines produced by the company. Cost data expressed in this empirical form can be useful in trade-off studies in the concept design phase. Parametric cost studies are often used in feasibility studies of large military systems. One must be careful not to use models of this type outside the range of data for which they apply.

Factor methods are related to parametric studies in that they use empirical relationships based on cost data to find useful predictive relationships. In Sec. 13.9 we presented a factor method for determining the unit manufacturing cost of a part.

$$C_u = VC_{mv} + P_c\left(C_{mp} \times C_c \times C_s \times C_{ft}\right) \tag{16.5}$$

where C_u is the manufacturing cost to make one unit of a part
V is the volume of the part
C_{mv} is the material cost per unit volume

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8. M. S. Peters, K. D. Timmerhaus, and R. E. West, *Plant Design and Economics for Chemical Engineers,* 5th ed., McGraw-Hill, New York, 2003.

P_c is the basic cost to process an ideal shape by a particular process
C_{mp} is a cost factor that indicates the relative ease with which a material can be shaped in a particular process
C_c is a relative cost associated with shape complexity
C_s is a relative cost associated with achieving minimy section thickness
C_{ft} is the cost of achieving a specified surface finish or tolerance.

It is important to understand that equations based on cost factors are not just made up in a haphazard fashion. Basic physics and engineering logic are carried as far as possible before employing empirical analysis of data. Equation (16.5) is aimed at estimating the cost to make a part in the conceptual design phase when many of the details of the features of the part have not been established. Its goal is to use part cost as a way of selecting the best process to make the part by including more design details than are included in the model for manufacturing cost described in Sec. 13.4.6. Equation (16.5) recognizes that material cost is often the main cost driver in part cost, so it separates this factor from those associated with the process. Here the cost equation introduces P_c, the basic processing cost for an "ideal shape." This factor aggregates all of the costs of production (labor, tooling, capital equipment, overhead) as a function of the production volume. Note that for a specific company, P_c could be decomposed into an equation representing its actual cost data. The factors in the parentheses are all factors that increase the cost over the ideal case.[9] Of these, shape complexity and tolerances (surface finish) have the greatest effect.

Models for developing cost for manufacturing use physics-based principles to determine such process parameters as the forces, flow rates, or temperatures involved. Eventually empirical cost factors are needed when dealing with process details. For example, the number of hours for machining a metal mold to be used in injection molding is given by[10] $M = 5.83(x_i + x_o)^{1.27}$ where x_i and x_o are contours of the inner and outer surfaces of the mold, respectively, and in turn, are given by x_i or $x_o = 0.1\,N_{SP}$ where N_{SP} is the number of surface patches or sudden changes in slope or curvature of the surface.

Factor methods of cost evaluation are used for estimating costs in the early stages of embodiment design and are employed in the concurrent costing software described in Sec. 13.9.

16.5.3 Detailed Methods Costing

Once the detailed design is completed and the final detailed drawings of the parts and assemblies have been prepared, it is possible to prepare a cost evaluation to ±5 percent accuracy. This approach is sometimes called methods analysis or the industrial engineering approach. The cost evaluation requires a detailed analysis of every operation to produce the part and a good estimate of the time required to complete the

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9. Building a model by starting with an ideal case and degrading it with individual factors is a common approach in engineering model building. In Sec. 12.3.4 we started with an ideal endurance limit and reduced its value by applying factors for stress concentration, diameter, and surface finish.

10. G. Boothroyd, P. Dewhurst, and W. Knight, *Product Design for Manufacture and Assembly,* 2d ed., pp. 362–64, Marcel Dekker, New York, 2002.

operation. A similar method is used to determine the costs of buildings and civil engineering projects.[11]

At the outset of developing the cost estimate, the following information should be available:

- Total quantity of product to be produced
- Schedule for production
- Detailed drawings and/or CAD file
- Bill of materials (BOM)

In complicated products the bill of materials may be several hundred lines. This makes it important that a system be in place to keep track of all parts and make sure none are left out of the cost analysis.[12] The BOM should be arranged in layers, starting with the assembled product, then the first layer of subassemblies, then the subassemblies feeding into this layer, all the way down to the individual parts. The total number of a given part in an assembled product is the number used at the lowest level multiplied by the number used at each other level of assembly. The total number of each part to be made or purchased is the number per product unit times the total number of products to be produced.

Detailed methods costing analysis is usually prepared by a process planner or a cost engineer. Such a person must be very familiar with the machines, tooling, and processes used in the factory. The steps to determine cost to manufacture a part are:

1. *Determine the material costs.* Since the cost of material makes up 50 to 60 percent of the cost of many products, this is a good place to start.

$$MtC = \frac{mC_{\mathrm{M}}}{(1-f)} \tag{16.6}$$

where C_M = cost of material in $/lb
m = weight of material, lb
f = fraction of material that ends up as scrap

Sometimes the cost of material is measured on a volume basis, and in other instances, as when machining bar stock, it might be measured per foot. Issues concerning the cost of materials were discussed in Sec. 11.5.

It is important to account for the cost of material that is lost in the form of scrap. Most manufacturing processes have an inherent loss of material. Sprues and risers that are used to introduce molten material into a mold must be removed from castings and moldings. Chip generation occurs in all machining processes, and metal stamping leaves unused sheet scrap. While most scrap materials can be recycled, there is an economic loss in all cases.

2. *Prepare the operations route sheet.* The route sheet is a sequenced list of all operations required to produce the part. An *operation* is a step in the process se-

11. Historical cost data is published yearly by R.S. Means Co. and in the *Dodge Digest of Building Costs.* Also see P.F. Ostwald, *Construction Cost Analysis and Estimating,* Prentice Hall, Upper Saddle River, NJ, 2001.

12. P.F. Ostwald, *Engineering Cost Estimating,* 3d ed., pp. 295–97, Prentice Hall, Upper Saddle River, NJ, 1992.

TABLE 16.1
A Sampling of Cycle-Time Elements

Operation Element	Minutes
Set up a lathe operation	78
Set up a drilling fixture	6
Brush away chips	0.14
Start or stop a machine tool	0.08
Change spindle speed	0.04
Index turret on turret lathe	0.03

quence, defined as all the work done on a machine or workstation. For example, an operation on an engine lathe might be to face the end of a bar, then rough turn the diameter to 0.610 in. and finish machine to 0.600. The *process* is the sequence of operations from the time the workpiece is taken from inventory until it is completed and placed in finished goods inventory. Part of developing the route sheet is to select the actual machine in the shop to perform the work. This is based on availability, the capacity to deliver the necessary force, depth of cut, or precision required by the part specification.

3. *Determine the time required to carry out each operation.* Whenever a new part is first made on a machine, there must be a *setup period* during which old tooling is taken out and new tooling is installed and adjusted. Depending on the process, this can be a period of minutes or several days, but two hours is a more typical setup time. Each process has a *cycle time,* which consists of loading the workpiece into the machine, carrying out the operation, and unloading the workpiece. The process cycle is repeated many times until the number of parts required for the batch size has been made. Often there is a downtime for shift change or for maintenance on the machine or tooling.

   Databases of standard times to perform small elements of typical operations are available.[13] Computer software with databases of operation times and cost calculation capability are available for most processes. If the needed information cannot be found in these sources, then carefully controlled time studies must be made.[14] A sampling of standard times for elements of operations is given in Table 16.1.

   An alternative to using standard times for operation elements is to calculate the time to complete an operation element with a physical model of the process. These models are well developed for machining processes[15] and for other manufacturing processes.[16] An example of the use of this method for metal cutting is given in Sec. 16.12.1.

13. P. F. Ostwald, *AM Cost Evaluator,* 4th ed., Penton Publishing Co., Cleveland, OH, 1988; W. Winchell, *Realistic Cost Estimating for Manufacturing,* 2d ed., Society of Manufacturing Engineers, Dearborn, MI, 1989.
14. B. Niebel and A. Freivalds, *Methods, Standards, and Work Design,* 11th ed., McGraw-Hill, New York, 2003.
15. G. Boothroyd and W. A. Knight, *Fundamentals of Machining and Machine Tools,* 2d ed., Chap. 6, Marcel Dekker, New York, 1989.
16. R. C. Creese, *Introduction to Manufacturing Processes and Materials,* Marcel Dekker, New York, 1999.

4. *Convert time to cost.* The times for each element in each operation are added to find the total time to complete each operation of the process. Then the time is multiplied by the fully loaded wage rate ($/h) to give the cost of labor. A typical product will require parts made by different processes, and some parts purchased rather than made in-house. Typically, different labor rates and overhead rates prevail in different cost centers of the factory.

EXAMPLE 16.6 A ductile cast iron V-belt pulley driven from a power shaft is made in a batch of 600 units. Its shape is similar to the object in the bottom left corner of category A1 in Fig. 13.18. The material cost is $50.00 per unit. Table 16.2 gives estimates of labor hours, labor rates, and overhead charges. Determine the unit product cost.

The estimates of the standard costs for the elements of each operation give the cycle time per 100 units given in column (2). In a similar way the setup costs for a batch are estimated in column (1) for each cost center. Multiplying (2) by 6 (the batch size is 600) plus adding in the setup cost gives the time to produce a batch of 600 units. With this and the wage rate (4), we determine the batch labor cost, column (5). The overhead cost for each cost center, based on a batch of 600 units, is given in (6). Adding (5) and (6) gives all of the in-house costs for that batch. These costs are placed on a per-unit basis in

TABLE 16.2
Process Plan for Ductile Iron Pulley (Batch Size 600 Units)

Cost Center	Operation	(1) Setup Time h/batch	(2) Cycle Time h/100 units	(3) Time to Finish Batch, h	(4) Wage Rate $/h	(5) Batch Labor Cost	(6) Batch Overhead	(7) Labor & Overhead Per Batch	(8) Unit Cost
Outsource	Purchase 600 units, rough castings, part no. 437837								$50.00
Machine shop—lathe	Total costs for operation	2.7	35	212.7	32.00	$6806	$7200	$14,006	$23.34
	1. Machine faces								
	2. Machine V-groove in OD								
	3. Rough machine hub								
	4. Finish machine ID of bore								
Machine Shop—drills	1. Drill and tap 2 holes for set screws	0.1	5	30.1	28.00	$843	$1050	$1893	$3.15
Finishing Dept.	Total cost for operation	6.3	12.3	80.1	18.50	$1482	$3020	$4502	$7.50
	1. Sand blast								
	2. Paint								
	3. Install 2 set screws								0.06
Totals		9.1	52.3	322.9		$9131	$11,616	$20,401	$84.05

(8). Note that the unit cost of $50.00 for the rough casting that was purchased from an outside foundry includes the overhead costs and profit for that company. The unit costs for the completed part developed in Table 16.2 do not include any profit, since that will be determined for the entire product for which the pulley is only one part.

Developing costs by an aggregated method is a lot of work, but computer databases and calculation aids make it much less of an onerous task than in the past. As already noted, this cost analysis requires a detailed process plan, which cannot be made until decisions on all of the design features, tolerances, and other parameters have been made. The chief drawback, then, is if a part cost turns out too high it may not be possible to make design changes to correct the problem. As a result, considerable effort is being given to cost methods that are capable of determining and controlling costs as the design process is being carried out. This topic, target costing, is discussed in Sec. 16.9.

16.6 MAKE-BUY DECISION

One of the uses of a detailed cost evaluation method such as was described in Example 16.6 is to decide whether it is less costly to manufacture a part in-house than to purchase it from an outside supplier. In that example, where the rough casting was bought from an outside foundry, it was decided that the volume of cast parts that will be used by the manufacturer does not justify the cost of equipping a foundry and hiring the expertise to make quality castings.

The parts that go into a product fall into three categories related to whether they should be made in-house or purchased from suppliers.

- Parts for which there is no in-house process capability obviously need to be purchased from suppliers.
- Parts that are critical to the quality of the product, involve proprietary manufacturing methods or materials, or involve a core technical competency need to be made in-house.
- Parts other than those in the previous categories, the majority of parts, offer no compelling reason to either use in-house manufacture or purchase from a supplier. The decision is usually based on which approach is least costly to obtain quality parts. Today the make-buy decision is being made not just with respect to suppliers in the vicinity of the manufacturer's plant, but in locations anywhere in the world where low-cost labor and manufacturing skill exist. This phenomenon of *offshoring* is made possible by rapid communication via the Internet and cheap water transportation with container ships. It has led to a boom in low-cost manufacturing of consumer goods in China and elsewhere in Asia.

Many factors other than cost enter into a make-buy decision.

Advantages of Outsourcing

- Lower cost of manufacture provides lower prime costs (materials and labor), especially with overseas suppliers.

- Suppliers can provide special expertise in design and manufacturing that the product developer may not have.
- Outsourcing provides increased manufacturing flexibility due to reduction in fixed costs. This lowers the breakeven point for a product.
- Manufacturing in a foreign country may result in access to a foreign market for the product.

Disadvantages of Outsourcing

- Outsourcing results in a loss of in-house design and manufacturing knowledge that is transferred to the supplier, and maybe to your competitors.
- It is more difficult to improve design for manufacture when in-house manufacturing capability is gone.
- Possible unsatisfactory quality
- In offshoring the supply chain is much longer. There is always a danger of delays in supply due to delay in gaining entry into port, strikes on the docks, and severe weather in transit.
- Also, offshoring may present such issues as currency exchange, communication in a different language and business culture, and the added expense in coordinating with an external supplier.

16.7 MANUFACTURING COST

Manufacturing costs begin to be determined in embodiment design as design details become firmed up. The methodology developed by Swift and coworkers at the University of Hull, and described in Sec. 13.9, and the Concurrent Costing software described in Example 13.7, are good examples of the tools available to make an early estimate of manufacturing cost.

Detailed manufacturing cost evaluation requires considerable specificity in dimensions, tolerances, materials, and process planning. See Example 16.6 for a simple example. This type of analysis cannot be done before detail design is complete and there is a bill of materials. Most commonly this is done in a process planning step that follows detail design. However, with the computerization of the costing process, it is becoming easier to move this process to a point earlier in the design process.

A basic equation for the cost of manufacturing a part was given in Sec. 13.4.6:

$$C_u = \frac{mC_M}{(1-f)} + \frac{C_L}{\dot{n}} + \frac{kC_T}{n} + \frac{1}{\dot{n}}\left(\frac{C_c}{\mathrm{L}t_{wo}}\right)q + \frac{C_{OH}}{\dot{n}} \qquad (16.7)$$

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This equation estimates the unit manufacturing cost for a part in terms of the material cost, labor cost, tooling cost, equipment cost, and overhead. See Sec. 13.4.6 for definition of terms and units. Equation (16.7) is used in the conceptual or early embodiment phase of design to select a process for making a part on the basis of relative cost. The equation requires no information about part features, but depends on process information that is usually available in general terms.

However, as seen in Example 16.6, when detailed cost estimates are made by aggregating the cost of operation elements, the accuracy of predictions is greatly increased, and the equation for unit product cost is more straightforward.

$$C_u = C_M + C_L + OH_F \tag{16.8}$$

where C_M is the material cost per unit, C_L is the labor cost per unit, and OH_F is the factory overhead.

The material cost includes the purchase cost of standard components, like bearings and gears, and the cost of raw material (bar stock, castings, etc.) from which the components are manufactured.

$$C_M = \left(\frac{Vc_m\rho}{1-f} + OH_m\right) + \left(B + OH_b\right) \tag{16.9}$$

where V is the volume of the part, c_m is the material cost per unit weight, ρ is the material density, and f is the fraction of scrap. OH_m is a material overhead to account for the procurement, inspection, storage, interest on this inventory, and material handling costs. B is the purchase cost of components and OH_b is the overhead on B.

The labor costs C_L depend on the time to complete all operations to make the part, $t_p = \Sigma t_0$. An overhead on labor cost is sometimes charged. OH_L is made up of time spent changing tools, lubricating, and similar activities, plus a nonproductive time allowance for time spent resting and waiting for parts.

$$C_L = t_p c_L + C_{su} + OH_L \tag{16.10}$$

where c_L is the direct labor wage rate, \$/h, and C_{su} is the total cost of machine setup for the process.

When overhead is broken out with respect to material cost and labor cost, as has been done in Eqs. (16.9) and (16.10), one must be careful not to double count overhead in Eq. (16.8). The accountants preparing the lists of indirect costs need to be aware of what charges, typically factory supervision and administration, go there, and what are charged to materials and labor. Typically in our examples we do not go to that level of detail.

16.8
PRODUCT PROFIT MODEL

An equation for estimating the cost to develop, manufacture, and market a consumer product is given in Eq. (16.11). Note that this equation does not give the cost for one unit of product, as we have typically done in this chapter, but rather calculates the product cost to produce a quantity of product units N_P.

$$C_p = N_p\left(C_M + C_L + OH_F\right) + T + M + OH_c + C_D \tag{16.11}$$

The bracketed terms in Eq. (16.11) are the same as in Eq. (16.8) and are variable costs. The other terms in Eq. (16.11) are fixed but not necessarily constant costs. T is the one-time costs for equipment and tooling. M is the marketing and sales costs, OH_C is corporate overhead costs, and C_D is the cost for developing the product and providing modest product updates.

We can now develop a simple profit model for the product.

$$\text{(1) Net sales} = (\text{number of units sold}) \times (\text{sales price}) \tag{16.12}$$

$$\text{(2) Cost of product sold} = (\text{number of units sold}) \times (\text{unit cost}) \tag{16.13}$$

$$\text{(3) Gross margin} = (1) - (2) = \text{Net sales} - \text{Cost of product sold} \tag{16.14}$$

$$\text{(4) Operating expenses} = \text{tooling} + \text{marketing} + \text{corp. OH} + \text{development} \tag{16.15}$$

$$\text{(5) Operating income (profit)} = (3) - (4) = \text{gross margin} - \text{operating expenses} \tag{16.16}$$

$$\text{Percentage profit} = (\text{profit/net sales}) \times 100 \tag{16.17}$$

Unit cost will be arrived at from Eq. (16.11) and by the methods discussed in Sec. 16.7. The number of units sold will be estimated by the marketing staff. Other costs will be provided by cost accounting or historical corporate records.

Note that the profit determined by the profit model is not the "bottom line" net profit found on the income statement of the annual report of a company. The net profit is the aggregate profit of many product development projects. To get from the operating income of a company to its net profit, many additional deductions must be made, the chief of which are the interest on borrowed debt and federal and state tax payments.

It is convenient to build the profit model with a computer-based spreadsheet program. Figure 16.3 shows a typical cost projection for a consumer product. Note that the sales price is projected to decline slightly as other competitors come into the market, but the sales volume is expected to increase over most of the life of the product as it gains acceptance through use by customers and advertising. This results in a nearly constant gross margin over the life of the product.

The development cost is broken out as a separate item in Fig. 16.3. The product was developed in a two-year period spread over 2002 to 2004. After that a modest annual investment was made in small improvements to the product. It is encouraging to see that the product was an instant hit and recovered its development cost in 2004, the year it was introduced to the market. This is a strong indication that the product development team understood the needs of the customer and satisfied them with its new product.

Considerable marketing and sales activity began the year of product introduction and are planned to continue at a high level throughout the expected life of the product. This is a reflection of the competition in the marketplace and the recognition that a company must be aggressive in placing its products before the customer. The "other" category in the spreadsheet mostly comprises factory and corporate overhead charges.

	Year								
	2002	2003	2004	2005	2006	2007	2008	2009	2010
Sales Price			$180.00	$178.00	$175.00	$173.00	$170.00	$168.00	$165.00
Unit Sales			100,000	110,000	120,000	130,000	130,000	120,000	110,000
Net Sales			$18,000,000	$19,580,000	$21,000,000	$22,490,000	$22,100,000	$20,160,000	$18,150,000
Unit Cost			$96.00	$95.00	$94.00	$93.000	$92.00	$92.00	$92.00
Cost of Product sold			$9,600,000	$10,450,000	$11,280,000	$12,090,000	$11,960,000	$11,040,000	$10,120,000
Gross Margin ($)			$8,400,000	$9,130,000	$9,720,000	$10,400,000	$10,140,000	$9,120,000	$8,030,000
Gross Margin (%)			46.67%	46.63%	46.29%	46.24%	45.88%	45.24%	44.24%
Development Cost	$750,000	$1,500,000	$750,000	$350,000	$350,000	$250,000	5250,000	$250,000	$250,000
Marketing			$2,340,000	$2,545,400	$2,730,000	$2,923,700	$2,873,000	$2,620,800	$2,359,500
Other			$2,160,000	$2,349,600	$2,520,000	$2,698,800	$2,652,000	$2,419,200	$2,178,000
Total Operating Expense	$750,000	$1,500,000	$5,250,000	$5,245,000	$5,600,000	$5,872,500	$5,775,000	$5,290,000	$4,787,500
Operating Income (Profit)	($750,000)	($1,500,000)	$3,150,000	$3,885,000	$4,120,000	$4,527,500	$4,365,000	$3,830,000	$3,242,500
Op Income (%)			17.50%	19.84%	19.62%	20.13%	19.75%	19.00%	17.87%
Cumulative Op Income	($750,000)	($2,250,000)	$900,000	$4,785,000	$8,905,000	$13,432,500	$17,797,500	$21,627,500	$24,870,000

Cumulative Sales	$141,480,000
Cumulative Gross Margin	$64,940,000
Cumulative Op Income	$24,870,000
Average % Gross Margin	45.90%
Average % Op Income	17.58%

FIGURE 16.3
Cost projections for a consumer product.

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TABLE 16.3
Trade-Off Decision Rules Based on Deviation from Baseline Conditions

Type of Shortfall	Baseline Oper. Income	Reduced Oper. Income	Cumulative Impact on Profit	Rule of Thumb
50% development cost overrun	$24,870,000	$23,370,000	−$1,500,000	$30,000 per %
5% overrun on product cost	$24,870,000	$21,043,000	−$3,827,000	$765,400 per %
10% reduction in sales due to performance issues	$24,870,000	$21,913,000	−$2,957,000	$295,700 per %
3-month delay in product introduction to market	$24,870,000	$23,895,000	−$957,000	$975,000 per %

Trade-off Studies

The four key objectives associated with developing a new product are:

- Bringing the cost of the product under the agreed-upon target cost.
- Producing a quality product that exceeds the expectation of the customer.
- Conducting an efficient product development process that brings the product to market, on schedule.
- Completing the development process within the approved budget for the product.

A product development team must recognize that not everything will go smoothly during the development process. There may be delays in the delivery of tooling, costs for outsourced components may increase because of higher fuel costs, or several parts may not interface according to specification. Whatever the reason, when faced with issues such as these, it is helpful to be able to estimate the impact of your plan to fix the problem on the profitability of your product. This is done by creating trade-off decision rules using the spreadsheet cost model.

Figure 16.3 represents the baseline profit model if everything goes according to plan. Other cost models can easily be determined for typical shortfalls from plan.

- A 50% cost overrun in development cost.
- A 5% cost overrun in unit cost.
- A 10% reduction in sales due to poor performance and customer acceptance.
- A 3-month delay in introducing the product into the marketplace.

Table 16.3 shows the impact on the cumulative operating income as a result of these changes from the baseline condition.

The trade-off *rule of thumb* is based on the assumption that changes are linear and each shortfall is independent of the others. For example, if a 10 percent decrease in sales causes a $2,957,000 reduction in cumulative operating profit, then a 1 percent decrease in sales will decrease operating profit by $295,700.

Note that the trade-off rules apply only to the particular case under study. They are not universal rules of thumb.

EXAMPLE 16.7 An engineer estimated that a savings of \$1.50 per unit could be made by eliminating the balancing operation on the fan of the product for which data is given in Table 16.3. However, marketing estimated there would be a 5 percent loss in sales due to increased vibration and noise of the product. Use the trade-off rules to decide whether the cost saving is a good idea.

Potential benefit: The unit cost is \$96.00. The percentage saving is 1.50/96 = 0.0156 = 1.56%

$$1.56 \times \$765{,}400(\text{per } 1\% \text{ change in unit cost}) = \$1{,}194{,}000$$

Potential cost: $5 \times \$295{,}700 = \$1{,}478{,}500$.

Benefit/cost is close but says that the potential cost in lost sales outweighs the savings. On the other hand, the estimate of lost sales of 5 percent is just an educated guess. One strategy might be to ask the engineer to do the cost saving estimate in greater detail, and if the cost saving holds up, make a trial lot that are sold in a limited geographic area where complaints and returns could be closely monitored. However, before doing this the product made without fan balancing needs to be carefully studied for noise and vibration with regard to OSHA requirements.

16.8.1 Profit Improvement

Three strategies commonly used to achieve increased profits are: (1) increased prices, (2) increased sales, (3) and reduced cost of product sold. Example 16.8 shows the impact of changes in these factors on the profit using the profit model described by Eqs. (16.11) to (16.17).

EXAMPLE 16.8 *Case A* is the current distribution of cost elements for the product.

Case B shows what would happen if price competition would allow a 5 percent increase in price without loss in units sold. The increased income goes right to the bottom line.

Case C shows what would happen if sales were increased by 5 percent. There would be a 5 percent increase in the four cost elements, while unit cost remains the same. Costs and profits rise to the same degree and percentage profit remains the same.

Case D shows what happens with a 5 percent productivity improvement (5 percent decrease in direct labor) brought about by a process-improvement program. The small increase in overhead results from the new equipment that was installed to increase productivity. Note that the profit per unit has increased by 10 percent.

Case E shows what happens with a 5 percent decrease in the cost of materials or purchased components. About 65 percent of the cost content of this product is materials. This cost reduction could result from a design modification that allows the use of a less expensive material or eliminates a purchased component. In this case, barring a costly development program, all of the cost savings goes to the bottom line and results in a 55 percent increase in the unit profit.

	Case A	Case B	Case C	Case D	Case E
Sales Price	$100	$105	$100	$100	$100
Units Sold	100	100	105	100	100
Net sales	$10,000	$10,500	$10,500	$10,000	$10,000
Direct labor	$1,500	$1,500	$1,575	$1,425	$1,500
Materials	$5,500	$5,500	$5,775	$5,500	$1,225
Overhead	$1,500	$1,500	$1,575	$1,525	$1,500
Cost of product sold	$8,500	$8,500	$8,925	$8,450	$8,225
Gross margin	$1,500	$2,000	$1,575	$1,550	$1,775
Total operating expenses	$1,000	$1,000	$1,050	$1,000	$1,000
Pretax profit	$500	$1,000	$525	$550	$775
Percentage profit	5%	9.5%	5%	5.5%	7.75%

A fourth profit improvement strategy, not illustrated by the example, is to upgrade the mix of products made and sold by the company. With this approach, greater emphasis is given to products with higher profit margins while gradually phasing out the product lines with lower profit margins.

16.9 REFINEMENTS TO COST ANALYSIS METHODS

Several refinements to cost estimating methods have appeared over the years aimed at giving more accurate cost evaluations. In this section we discuss (1) adjustments for cost inflation, (2) relationships between product or part size and cost, and (3) reduction in manufacturing costs because of learning.

16.9.1 Cost Indexes

Because the purchasing power of money decreases with time, all published cost data are out of date. To compensate for this, cost indexes are used to convert past costs to current costs. The cost at time 2 is the cost at time 1 multiplied by the ratio of the cost indexes.

$$C_2 = C_1\left(\frac{\text{Index @ time 2}}{\text{Index @ time 1}}\right) \tag{16.18}$$

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The most readily available cost indexes are:

- Consumer Price Index (CPI)—gives the price of consumer goods and services
- Producer Price Index (PPI)—measures the entire market output of U.S. producers of goods. The Finished Goods Price Index of the PPI is roughly split between du-

rable goods (not in the CPI) and consumer goods. No services are measured by the PPI. Both the CPI and PPI are available at www.bls.gov.

- The *Engineering News Record* provides indexes on general construction costs.
- The Marshall and Swift Index, found on the last page of *Chemical Engineering* magazine, provides an index of industrial equipment costs. The same magazine publishes the Chemical Engineering Plant Equipment Index, which covers equipment such as heat exchangers, pumps, compressors, piping, and valves.

Many trade associations and consulting groups also maintain specialized cost indexes.

EXAMPLE 16.9 An oilfield diesel engine cost \$5500 when it was purchased in 1982. What did it cost to replace the diesel engine in 1997?

$$C_{1997} = C_{1982}\left(\frac{I_{1997}}{I_{1982}}\right) = 5500\left(\frac{1156.8}{121.8}\right) = 5500(1.29) = \$7095$$

What did it cost to replace the engine in 2006 if the *finished goods price index* for oil and gas field machinery was 210.3?

$$C_{2006} = C_{1997}\left(\frac{210.3}{156.8}\right) = 7095(1.34) = \$9516$$

We see there was an average increase in price of 1.9 percent over the first 15 years, and a 3.8 percent yearly average over the last 9 years. This is a reflection of the rapid acceleration of oil and gas business in the recent past. Similar calculations for the automobile parts business would see hardly any price increase since 1997, an indication of the fierce competition in this relatively stagnant market.

You should be aware of some of the pitfalls inherent in using cost indexes. First, you need to be sure that the index you plan to use pertains to the problem you must solve. The cost indexes in the *Engineering News Record* index would not apply to estimating costs of computer parts. Also, the indexes are aggregate values, and do not generally pertain to a particular geographic area or labor market. Of more basic concern is the fact that the cost indexes reflect the costs of past technology and design procedures.

16.9.2 Cost-Size Relationships

The cost of most capital equipment is not directly proportional to the size or capacity of the equipment. For example, doubling the horsepower of a motor increases the cost by only about one-half. This *economy of scale* is an important factor in engineering design. The cost-capacity relation usually is expressed by

$$C_1 = C_0\left(\frac{L_1}{L_0}\right)^x \qquad (16.19)$$

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where C_0 is the cost of equipment at size or capacity L_0. The exponent x varies from about 0.4 to 0.8, and it is approximately 0.6 for many items of process equipment. For

TABLE 16.4
Typical Values of Size Exponent for Equipment

Equipment	Size Range	Capacity Unit	Exponent x
Blower, single stage	1000–9000	ft^3/min	0.64
Centrifugal pumps. S/S	15–40	hp	0.78
Dust collector, cyclone	2–7000	ft^3/min	0.61
Heat exchanger, shell and tube, S/S	50–100	ft^2	0.51
Motor, 440- V, fan-cooled	1–20	hp	0.59
Pressure vessel, unfired carbon steel	6000–30,000	lb	0.68
Tank, horizontal, carbon-steel	7000–16,000	lb	0.67
Transformer, 3-phase	9–45	kW	0.47

Source: R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook,* 5th ed., p. 25–18, McGraw-Hill, New York, 1973.

that reason, the relation in Eq. (16.19) often is referred to as the "six-tenths rule." Values of x for different types of equipment are given in Table 16.4.

Logically, cost indexes can be combined with cost-size relationships to provide for cost inflation as well as economy of scale.

$$C_1 = C_0 \left(\frac{L_1}{L_0} \right)^x \left(\frac{I_1}{I_0} \right) \tag{16.20}$$

The six-tenths rule applies only to large process or factory-type equipment. It does not apply to individual machine parts or smaller kinds of mechanical systems like transmissions. To a first approximation, the material cost of a part, *MtC,* is proportional to the volume of the part, which in turn is proportional to the cube of a characteristic dimension, *L*. Thus, the material cost increases as a power of its dimension.

$$MtC_1 = MtC_0 \left(\frac{L_1}{L_0} \right)^n \tag{16.21}$$

where n was found for steel gears to be 2.4 in the range of diameters from 50 to 200 mm and $n = 3$ for diameters from 600 to 1500 mm.[17]

In another example of a cost growth law, the production cost, *PC*, for machining, based on time to complete an operation, might be expected to vary with the surface area of the part, i.e., with L.[2]

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$$PC_1 = PC_0 \left(\frac{L_1}{L_0} \right)^p \tag{16.22}$$

17. K. Erlenspiel, et al., *Cost-Efficient Design,* p. 161, Springer, New York, 2007.

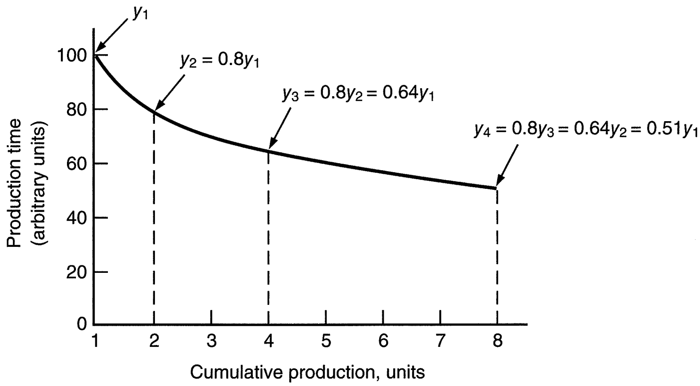

FIGURE 16.4
An 80 percent learning curve.

Again, p depends on processing condition. The exponent is 2 for finish machining and grinding and 3 for rough machining, where the depth of cut is much deeper.

Information about how processing cost depends on part size and geometry is very scanty. This information is needed to find better ways to calculate part cost early in the design process as different features and part sizes are being explored.

16.9.3 Learning Curve

A common observation in a manufacturing situation is that as the workers gain experience in their jobs they can make or assemble more product in a given unit of time. That, of course, decreases costs. This learning is due to an increase in the worker's level of skill, to improved production methods that evolve with time, and to better management practices involving scheduling and other aspects of production planning. The extent and rate of improvement also depend on such factors as the nature of the production process, the standardization of the product design, the length of the production run, and the degree of harmony in worker- management relationships.

The improvement phenomenon usually is expressed by a *learning curve*, also called a product improvement curve. Figure 16.4 shows the characteristic features of an 80 percent learning curve. Each time the cumulative production doubles ($x_1 = 1$, $x_2 = 2$, $x_3 = 4$, $x_4 = 8$, etc.) the production time (or production cost) is 80 percent of what it was before the doubling occurred. For a 60 percent learning curve the production time would be 60 percent of the time before the doubling. Thus, there is a constant percentage reduction for every doubled[18] production. Such an obviously exponential curve will become linear when plotted on loglog coordinates (Fig. 16.5).

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18. The learning curve could be constructed for a tripling curve of production or any other amount, but it is customary to base it on a doubling.

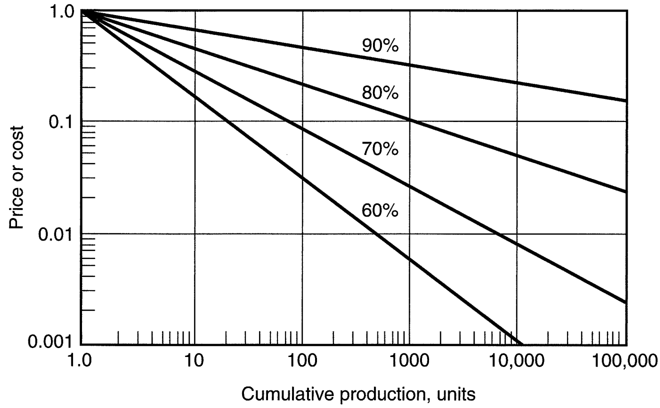

FIGURE 16.5
Standard learning curves.

Note that a 60 percent learning curve gives a greater cost reduction than an 80 percent learning curve.

The learning curve is expressed by

$$y = kx^n \tag{16.23}$$

where y is the production effort, expressed either as h/unit or \$/unit
k is the effort to manufacture the first unit of production
x is the unit number, that is, $x = 5$ or $x = 45$
n is the negative slope of the learning curve, expressed as a decimal. Value for n are given in Table 16.5.

The value for n can be found as follows: For an 80 percent learning curve, $y_2 = 0.8y_1$ for $x_2 = 2x_1$. Then,

$$\frac{y_2}{y_1} = \left(\frac{x_2}{x_1}\right)^n$$

$$\frac{0.8y_1}{y_1} = \left(\frac{2x_1}{x_1}\right)^n$$

$$n \log 2 = \log 0.8$$

$$n = \frac{-0.0969}{0.3010} = -0.322$$

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Note that the learning curve percentage, expressed as a decimal, is $P = 2^n$.

EXAMPLE 16.10 The first of a group of 80 machines takes 150 h to build and assemble. If you expect a 75 percent learning curve, how much time would it take to complete the fortieth machine and the last machine?

TABLE 16.5
Exponent Values for Typical Learning Curve Percentages

Learning Curve Percentages, *P*	*n*
65	−0.624
70	−0.515
75	−0.415
80	−0.322
85	−0.234
90	−0.152

TABLE 16.6
Based on an 80 Percent Learning Curve

x units	*y*, h/unit	Cumulative Total Hours	*y*, Cumulative Average h/unit
1	100.00	100.00	100.00
2	80.00	180.00	90.00
3	70.22	250.22	83.41
4	64.00	314.22	78.55
5	59.56	373.78	74.76
6	56.16	429.94	71.66
7	53.44	483.38	69.05
8	51.19	534.57	66.82

$y = kx^n$

For $P = 75\%$, $n = -0.415$, and $k = 150$

$$y = 150\left(x^{-0415}\right)$$

For $x = 40$

$$y_{40} = 150\left(40^{-0.415}\right) = 32.4\,\text{h}$$

For $x = 80$

$$y_{80} = 150\left(80^{-0.415}\right) = 24.3\,\text{h}$$

The learning curve can be expressed as the production time in hours to produce a particular number unit or as the cumulative average hours to make *N* units. The latter term is usually of more interest in cost evaluation. The distinction between these two ways of expressing the output is shown in Table 16.6. Note that, for a given number of units of output, the cumulative average is greater than the unit values. However, the learning improvement percentage (80 percent) that applies to the unit values does not apply to the cumulative values. Similarly, if the unit values are derived from cumulative values, the constant percentage does not apply. In constructing learning curves from historical data we are more likely to find records of cumulative total hours than the hours to build each unit.

The total hours, T_c, required to manufacture a cumulative total of N units is given by

$$T_c = y_1 + y_2 + \dots y_N = \sum_{i=1}^{N} \tag{16.24}$$

The average time to produce N parts, T_a, is

$$T_a = \frac{T_c}{N} \tag{16.25}$$

An approximation for Eq. (16.25) when N is greater than 20 is

$$T_a \simeq \frac{1}{(1-n)} kN^n \tag{16.26}$$

16.10 DESIGN TO COST

Design to cost, also called *target costing*, is the approach in which a target value, (sometimes called "should-cost" data), for the cost of a product is established at the beginning of a product development project. All design decisions are examined for their impact on keeping below the target cost. This is in contrast with the more usual practice of waiting for a complete cost analysis in the detail design phase. If this proves to be excessive, then the only practical recourse is to try to wring the excess cost out of the manufacturing process or to substitute a less expensive material, often at the expense of quality.

The steps in accomplishing design to cost are:[19]

- *Establish a realistic and reliable target cost.* The target cost is the difference between a realistic estimate of what the customer will pay for the product when developed minus the expected profit. This requires effective and realistic market analysis and an agile product development process that gets the product to market in minimum time.
- *Divide the target cost into subunits.* The basis for dividing the total cost can be (1) cost of subsystems and components in similar designs, (2) division according to competitors' component costs, or (3) on the basis of estimates of what the customer is willing to pay for various functions and features of the product.
- *Oversight of compliance with cost targets.* A major difference in the design to cost approach is that the cost projections will be evaluated after each design phase and before going into production. For this to be effective there must be cost evaluation methods that can be applied at an earlier stage than detail design. There must also be a systematic way of quickly making cost comparisons.

19. K. Ehrlenspiel et al., op. cit., pp. 44–63.

16.10.1 Order of Magnitude Estimates

At the very early stage of product development where the market for a new product is being studied, comparison is usually made with similar products already on the market. This gives bounds on the expected selling price. Often the cost is estimated with a single factor. Weight is most commonly used. For example,[20] products can be divided roughly into three categories:

1. Large functional products—automobile, front-end loader, tractor
2. Mechanical/electrical—small appliances and electrical equipment
3. Precision products—cameras, electronic test equipment

Products in each category cost about the same on a weight basis, but the cost between categories increases by a factor of approximately 10. An automobile is about \$5 per pound, a high-end blender is about \$50 per pound, and an automatic digital camera is about \$500 per pound.

A slightly more sophisticated method is to estimate cost on the basis of the percentage of the share of the total cost that is due to materials cost.[21] For example, about 70 percent of the cost of an automobile is material cost, about 50 percent for a diesel engine, about 25 percent for electrical instruments, and about 7 percent for china dinnerware.

EXAMPLE 16.11 What is the total cost of a diesel engine that weighs 300 lb? The engine is made from ductile iron that costs \$2/lb. The material cost share for the engine is 0.5.

$$\text{Cost} = (300 \times \$2)/0.5 = \$1200$$

Another rule of thumb is the one-three-nine rule.[22] This states the relative proportions of material cost (1), manufacturing cost (3), and selling price (9). In this rule the material cost is inflated by 20 percent to allow for scrap and tooling costs.

EXAMPLE 16.12 A 2 lb part is made from an aluminum alloy costing \$1.50/lb. What is the estimated material cost, part cost, and selling price?

$$\text{Material cost} = 1.2 \times 1.50\ \$/\text{lb} \times 2\ \text{lb} = \$3.60$$

$$\text{Part cost} = 3 \times \text{material cost} = 3 \times \$3.60 = \$10.80$$

$$\text{Selling price} = 3 \times \text{part cost} = 3 \times \$10.80 = \$32.40 \text{ or}$$

$$\text{Selling price} = 9 \times \text{material cost} = 9 \times \$3.60 = \$32.40$$

16.10.2 Costing in Conceptual Design

At the conceptual design stage, few details have been decided about the design. Costing methods are required that allow for direct comparison between different types of designs that would perform the same functions. An accuracy of ±20 percent is the goal.

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20. R. C. Creese, M. Adithan, and B. S. Pabla, *Estimating and Costing for the Metal Manufacturing Industries,* Marcel Dekker, New York, 1992, p. 101.
21. R. C. Creese et al., op. cit., pp. 102–5.
22. H. F. Rondeau, *Machine Design,* Aug. 21, 1975, pp. 50–53.

Relative costs are often used for comparing the costs of different design configurations, standard components, and materials. The base cost is usually the cost of the lowest-cost or most commonly used item. An advantage of relative cost scales is that they change less with time than do absolute costs. Also, there are fewer problems with proprietary issues with relative costs. Companies are more likely to release relative cost data than they are absolute costs.

Parametric methods work well where designs tend to be variants of earlier designs. The costing information available at the conceptual design stage usually consists of historical cost for similar products. For example, cost equations for two- engine small airplanes have been developed,[23] and similar types of cost relationships exist for coal-fired power plants and many types of chemical plants. However, for mechanical products, where there is a wide diversity of products, few such relationships have been published. This information undoubtedly exists within most product manufacturing companies.

Cost calculations in conceptual design must be done quickly and without the amount of cost detail used in Example 16.6. One saving grace is that not all parts in a product will require cost analysis. Some parts may be identical to parts in other products, for which the cost is known. Other parts are standard components or are parts that will be outsourced, and the costs are known with a firm quotation. An additional group of parts will be similar parts that differ only by the addition or subtraction of some physical features. The cost of these parts will be the cost of the original part plus or minus the cost of the operations to create the features that are different.

For those parts that require a cost analysis, "quick cost calculations" are used. The development of quick cost methods is an ongoing activity, chiefly in Germany.[24] The methods are too extensive to detail here, other than to give an example of an equation for scaling unit manufacturing cost C_u from size L_0 to size L_1.

$$C_u = \frac{PCsu}{n}\left(\frac{L_1}{L_0}\right)^{0.5} + PCt_0\left(\frac{L_1}{L_0}\right)^2 + MtC_0\left(\frac{L_1}{L_0}\right)^3 \tag{16.27}$$

In the equation, $PCsu$ is the processing cost for tool setup, PCt_0 is the processing cost for the original part based on total operation time, and MtC_0 is the material cost for the original size L_0.

An intellectually satisfying approach to determining costs early in design is functional costing.[25] The idea behind this approach is that once the functions to be performed have been determined, the minimum cost of the design has been fixed. Since it is in conceptual design that we identify the needed functions and work with alternative ways of achieving them, linking functions to cost gives us a direct way of designing to cost. A start has been made with standard components like bearings, electric motors, and linear actuators, where the technology is relatively mature and costs have become rather competitive. Linking function with cost is the basic idea behind value analysis. This is discussed in the next section.

23. J. Roskam, *J. Aircraft,* Vol. 23, pp. 554–60, 1986.
24. K. Ehrlenspiel, op. cit., pp. 430–56.
25. M. J. French, *Jnl. Engr. Design,* Vol. 1, No. 1, pp. 47–53, 1990; M. J. French and M. B. Widden, *Design for Manufacturability 1993, DE,* Vol. 52, pp. 85–90, ASME, New York, 1993.

Probably the greatest progress in finding ways to determine cost early in the design process is with the use of special software. A number of software programs that incorporate quick design calculations, cost models of processes, and cost catalogs are available. Some sources where you can find additional information are:

- *SEER DFM* by Galorath[26] uses advance parametric modeling to estimate manufacturing costs early in the design process. The software is able to deal with the following processes: machining, casting, forging, molding, powder metals, heat treatment, coating, fabrication of sheet metal, composite materials, printed circuit boards, and assembly. *SEER-H* provides system-level cost analysis and management in product development from work breakdown structure to the cost of operation and maintenance.
- *DFM Concurrent Costing* by Boothroyd Dewhurst[27] was discussed in Sec. 13.10.2. This software requires minimum part detail to provide relative costs for process selection.
- *Feature-Based Cost Analytics* (FBCA) by Akoya Inc[28] uses predictive cost data models based on data mining thousands of parts with known manufacturing costs. The parametric equations include financial information, purchasing information, and part attributes such as part weight and volume, type of material, heat treating, and required geometric tolerances.
- *Costimator* by MTI Systems[29] provides detailed cost estimates for parts made by machining. As one of the early suppliers in this field, its software contains extensive cost models, labor standards, and material cost data. It specializes in providing a fast, accurate, and consistent method that allows job shops to estimate cycle times and costs for preparing quotations.

16.11 VALUE ANALYSIS IN COSTING

Value analysis[30] is concerned with breaking a product into its component parts to determine the value of these design elements. Success with value analysis depends on understanding the relationship of each design feature and the function it provides. Value analysis is used most frequently in looking at how a product could be redesigned to reduce cost.

EXAMPLE 16.13 Table 16.7 shows the cost structure for a centrifugal pump.[31] In this table the components of the pump have been classified into three categories, A, B, and C, according to their manufacturing costs. Components in class A comprise 82 percent of the total cost. These "vital few" need to be given the greatest thought and attention.

26. www.galorath.com
27. www.dfma.com
28. www.akoyainc.com
29. www.mtisystems.com
30. T. C. Fowler, *Value Analysis in Design,* Van Nostrand Reinhold, New York, 1990.
31. M. S. Hundal, *Systematic Mechanical Design,* ASME Press, New York, 1997, pp. 175, 193–96.

TABLE 16.7
Cost Structure for a Centrifugal Pump

Cost Category	Part	Manufacturing Cost $	Manufacturing Cost %	Type of Cost, % Material	Type of Cost, % Production	Type of Cost, % Assembly
A	Housing	5500	45.0	65	25	10
A	Impeller	4500	36.8	55	35	10
B	Shaft	850	7.0	45	45	10
B	Bearings	600	4.9	Purchased	Purchased	Purchased
B	Seals	500	4.1	Purchased	Purchased	Purchased
B	Wear rings	180	1.5	35	45	20
C	Bolts	50	<1	Purchased	Purchased	Purchased
C	Oiler	20	<1	Purchased	Purchased	Purchased
C	Key	15	<1	30	50	20
C	Gasket	10	<1	Purchased	Purchased	Purchased

From M. S. Hundal, *Systematic Mechanical Design,* ASME Press, New York, 1997. Used with permission.

TABLE 16.8
Functions Provided by Each Component of the Centrifugal Pump

Function	Description	Components
F1	Contain liquid	Housing, seals, gasket
F2	Transfer energy	Impeller, shaft, key
F3	Convert energy	Impeller
F4	Connect parts	Bolts, key
F5	Increase life	Wear rings, oiler
F6	Support parts	Housing, shaft, bearings

From M. S. Hundal, *Systematic Mechanical Design,* ASME Press. Used with permission.

We now focus attention on the functions provided by each component of the pump (Table 16.8). This table of functions is added to the cost allocation table to create Table 16.9. Note that an estimate has been made of how much each component contributes to each function. For example, the shaft contributes 60 percent to transfer of energy (F2) and 40 percent to supporting the parts (F6). Multiplying the cost of each component by the fraction it serves to provide a given function gives the total cost for each function. For example, the function support parts (F6) is provided partly by the housing, shaft, and bearings.

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$$\text{Cost of F6} = 0.5(5500) + 0.4(850) + 1.0(600) = \$3690$$

These calculations are summarized in Table 16.10. This table shows that the expensive functions of the pump are containing the liquid, converting the energy, and supporting the parts. Thus, we know where to focus attention in looking for creative solutions in reducing costs in the design and manufacture of the pump.

TABLE 16.9
Cost Structure for Centrifugal Pump with Function Cost Allocation

Cost Class	Part	Manufacturing Cost $	Manufacturing Cost %	Type of Cost, % Material	Type of Cost, % Production	Type of Cost, % Assembly	Function Allocation, %			
A	Housing	5500	45.0	65	25	10	F1	50	F6	50
A	Impeller	4500	36.8	55	35	10	F2	30	F3	70
B	Shaft	850	7.0	45	45	10	F2	60	F6	40
B	Bearings	600	4.9	Purchased	Purchased	Purchased	F6	100		
B	Seals	500	4.1	Purchased	Purchased	Purchased	F1	100		
B	Wear rings	180	1.5	35	45	20	F5	100		
C	Bolts	50	<1	Purchased	Purchased	Purchased	F4	100		
C	Oiler	20	<1	Purchased	Purchased	Purchased	F5	100		
C	Key	15	<1	30	50	20	F2	80	F4	20
C	Gasket	10	<1	Purchased	Purchased	Purchased	F1	100		

From M. S. Hundal, *Systematic Mechanical Design,* ASME Press, New York, 1997. Used with permission.

TABLE 16.10
Calculation of Function Costs for Centrifugal Pump

Function	Part	% of Part Cost for Function	Part Cost, $	Function Cost of Individual Part, $	Total Function Cost $	Total Function Cost %
F1: Contain Liquid	Housing	50	5500	2750		
	Seals	100	500	500		
	Gasket	100	10	10	3260	26.7
F2: Transfer Energy	Impeller	30	4500	1350		
	Shaft	60	850	510		
	Key	80	15	12	1872	15.3
F3: Convert Energy	Impeller	70	4500	3150	3150	25.8
F4: Connect Parts	Key	20	15	3		
	Bolts	100	50	50	53	0.4
F5: Increase Life	Wear rings	100	180	180		
	Oiler	100	20	20	200	1.6
F6: Support Parts	Housing	50	5500	2750		
	Shaft	40	850	340		
	Bearings	100	600	600	3690	30.2

From M. S. Hundal, *Systematic Mechanical Design,* ASME Press. New York, 1997. Used with permission.

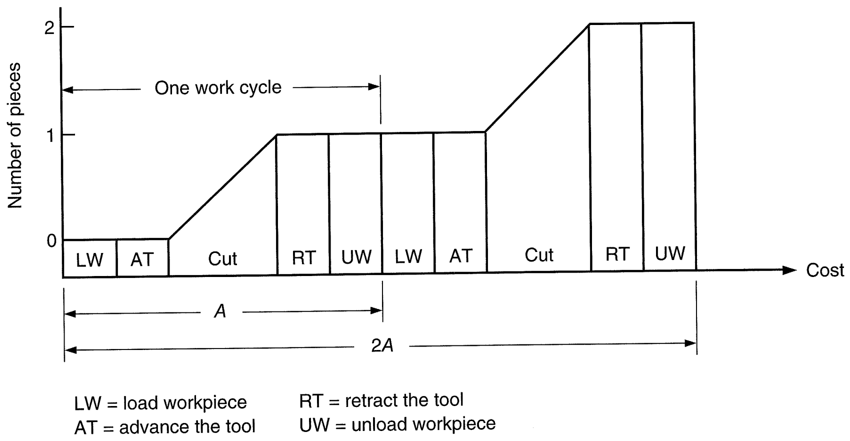

FIGURE 16.6
Elements of a machining operation.

16.12 MANUFACTURING COST MODELS

The importance of modeling in the design process was illustrated in Chap. 10. Modeling can show which elements of a design contribute most to the cost; that is, it can identify cost drivers. With a cost model it is possible to determine the conditions that minimize cost or maximize production (cost optimization). We have already seen that cost models aid significantly in the selection of which process to use to make a part.

16.12.1 Machining Cost Model

Extensive work has been done on cost models for metal removal processes.[32] Broken down into its simplest cost elements, a machining process can be described by Fig. 16.6. The time designated A is the machining plus work-handling costs per piece. If B is the tool cost, including the costs of tool changing and tool grinding, in dollars per tool, then

$$\text{Cost/piece} = \frac{nA + B}{n} = A + \frac{B}{n} \qquad (16.28)$$

where n is the number of pieces produced per tool.

16

32. E. J. A. Armarego and R. H. Brown, *The Machining of Metals,* Chap. 9, Prentice Hall, Englewood Cliffs, NJ, 1969; G. Boothroyd and W. A. Knight, *Fundamentals of Machining and Machine Tools,* 3d ed., CRC Press, Beca Raton, FL, 2006.

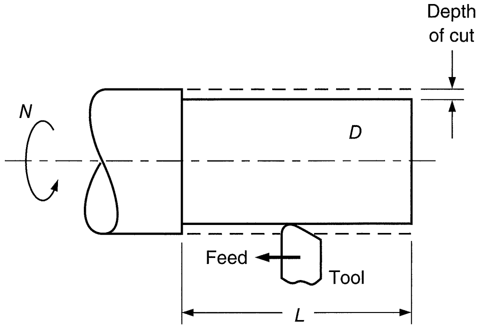

FIGURE 16.7
Details of lathe turning.

We shall now consider a more detailed cost model for turning down a bar on a lathe (Fig. 16.7). The machining time for one cut, t_c, is

$$t_c = \frac{L}{V_{feed}} = \frac{L}{fN} = \frac{L}{f}\frac{D}{12v} \tag{16.29}$$

where V_{feed} = feed velocity, in. /min
f = feed rate, in. /rev
N = rotational velocity, rev/min
D = work diameter, in.
v = cutting velocity, ft/mm

Equation (16.29) holds in detail only for the process of turning a cylindrical bar. For other geometries or other processes such as milling or drilling, different expressions would be used for L or V_{feed}.

The total cost of a machined part is the sum of the machining cost C_{mc}, the cost of the cutting tools, C_t, and the cost of the material C_m.

$$C_u = C_{mc} + C_t + C_m \tag{16.30}$$

where C_u is the total unit (per piece) cost. The machining cost, C_{mc} (\$/h), depends on the machining time t_{unit} and the costs of the machine, labor, and overhead.

$$C_{mc} = \left[M\left(1+OH_m\right) + W\left(1+OH_{op}\right)\right]t_{unit} \tag{16.31}$$

where M is maching cost rate, \$/h
OH_m is machine overhead rate, decimal
W is labor rate for machine operator, \$/h
OH_{op} is operator overhead rate, decimal

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The machine cost includes the cost of interest, depreciation, and maintenance. It is found with the methods of Chap. 18 by determining these costs on an annual basis and converting them to per-hour costs on the basis of the number of hours the machine is used in the year. The machine overhead cost includes the cost of power and other services and a proportional share of the building, taxes, insurance, and other such expenses.

The production time for a unit is the sum of the machining time t_m and the non-production or idle time t_i.

$$t_{unit} = t_m + t_i \tag{16.32}$$

The machining time t_m is the machining time for one cut, t_c, multiplied by the number of cuts.

$$t_m = t_c \left(\text{number of cuts}\right) \tag{16.33}$$

The idle time is given by

$$t_i = t_{set} + t_{change} + t_{hand} + t_{down} \tag{16.34}$$

where t_{set} = total time fo job setup divided by number of parts in the batch
t_{change} = prorated time for changing the cutting tool

$$= \text{tool change time} \times \frac{t_m}{\text{tool life}}$$

t_{hand} = time the maching operator spends loading and unloading the work on the machine
t_{down} = downtime lost because of machine or tool failure, waiting for material or tools, or maintenance operations, Downtime is prorated per units production.

An important cost component is the cost of cutting tools. Tools lose their cutting edge from the extreme wear and high temperature generated at the tool-metal interface. The cost of tooling is the cost of cutting tools and a prorated cost of special fixtures used to hold the tool bits. The cost of the cutting tool per unit piece is

$$C_t = C_{tool} \frac{t_m}{T} \tag{16.35}$$

where C_{tool} is the cost of a cutting tool, \$
t_m is the machining time (min), given by Eq. (16.33)
T is the tool life (min) given by Eq. (16.36)

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Tool life usually is expressed by the Taylor tool life equation, which relates tool life T to surface velocity v.

$$vT^p = K \tag{16.36}$$

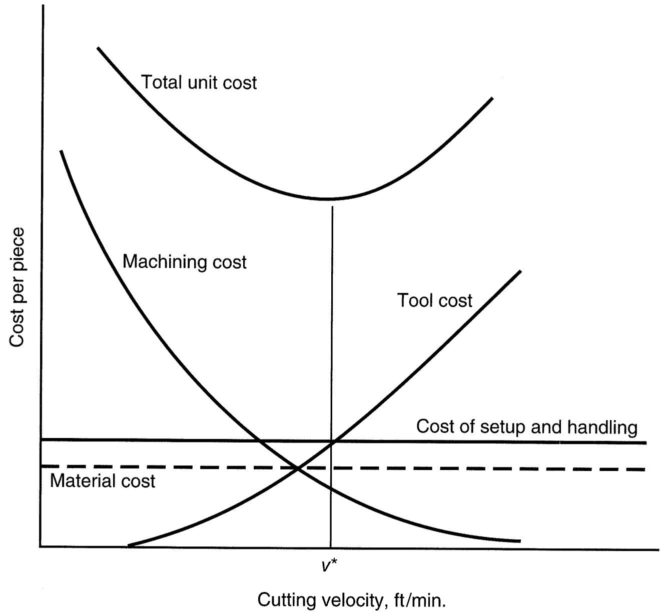

FIGURE 16.8
Variation of unit cost with cutting velocity, showing an optimum cutting velocity.

A log-log plot of tool life (min) versus surface velocity (ft/min) will give a straight line. K is the surface velocity at $T = 1$ min and p is the reciprocal of the negative slope.

For a cutting tool that uses an insert in a tool holder,

$$C_{tool} = \frac{K_i}{n_i} + \frac{K_h}{n_h} \qquad (16.37)$$

where K_i is the cost of one tool insert, \$
n_i is the number of cutting edges on a tool insert.
K_h is the cost of a tool holder, \$
n_h is the number of cutting edges in the life of a tool holder

Substituting the tool life T from Eq. (16.36) into Eq. (16.35) gives

$$C_t = C_{tool} t_m \left(\frac{v}{K} \right)^{1/p} \qquad (16.38)$$

The time needed to change tools can be significant, so we separate it out as t_{tool} from the other times listed in Eq. (16.34).

$$t_{change} = t_{tool}\left(\frac{t_m}{T}\right) \tag{16.39}$$

The other three terms in Eq. (16.34) are independent of tool life, and are designated by t_0. The expression for the time to machine one piece, Eq. (16.32), now can be written as

$$t_{unit} = t_m + t_i = t_m + t_{change} + t_0 = t_m + t_{tool}\frac{t_m}{T} + t_0 = t_m\left(1 + \frac{t_{tool}}{T}\right) + t_0 \tag{16.40}$$

Substituting Eqs. (16.31), (16.40), and (16.35) into Eq. (16.30) gives

$$C_u = \left[M\left(1 + OH_m\right) + W\left(1 + OH_{op}\right)\right]\left[t_m\left(1 + \frac{t_{tool}}{T}\right) + t_0\right] + C_t\frac{t_m}{T} + C_m \tag{16.41}$$

This equation gives the cost of a unit machined piece. Both the machining time, t_m, and the tool life, T, depend on the cutting velocity through Eqs. (16.33), (16.29), and (16.36). If we plot unit cost versus cutting velocity (Fig. 16.8), there will be an optimum cutting velocity to minimize cost. That is so because machining time decreases with increasing velocity; but as velocity increases, tool wear and tool costs increase also. Thus, there is an optimum cutting velocity. An alternative strategy would be to operate at the cutting speed that results in maximum production rate. Still another alternative is to operate at the speed that maximizes profit. The three criteria do not result in the same operating point.

The machining cost model illustrates how a physical model of the process, along with standard times for elements of the operation, can be used to determine realistic part costs. Also, the problem shows how overhead costs can be allocated to both labor and material costs. Compare this with the approach given in Sec 16.3 where a single factory overhead cost was used.

The machining cost model is based chiefly on physical models. When a good physical model is not available the process still can be broken down into discrete steps, with times and costs for each step. The procedure for this can be found under Process Cost Modeling on the website for this text (www.mhhe.com/dieter).

16.13 LIFE CYCLE COSTING

Life cycle costing (LCC) is a methodology that attempts to capture all of the costs associated with a product throughout its life cycle.[33] A typical problem is whether it is more economical to spend more money in the initial purchase to obtain a product

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33. R. J. Brown and R. R. Yanuck, *Introduction of Life Cycle Costing,* Prentice Hall, Englewood Cliffs, NJ, 1985; W. J. Fabrycky and B. S. Blanchard, *Life-Cycle Cost and Economic Analysis,* Prentice Hall, Englewood Cliffs, NJ, 1991.

with lower operating and maintenance costs, or whether it is less costly to purchase a product with lower first costs but higher operating costs. Life cycle costing goes into the analysis in much detail in an attempt to evaluate all relevant costs, both present and future.

The costs that enter into life cycle costing can be divided into five categories.

- *First costs.* Purchase cost of equipment or plant.
- *One-time costs.* Cost for transportation, installation, training of operating personnel, startup, and hazardous material cleanup and disposal of equipment upon retirement.
- *Operating costs.* Wages for production or operating personnel, utilities, supplies, materials, disposal of hazardous materials.
- *Maintenance costs.* Cost for service, inspection, and repair or replacement of equipment.
- *Other costs.* Taxes and insurance.

Life cycle costing, also known as "whole life costing," first found strong advocates in the area of military procurement, where it is used to compare competing weapons systems.[34] A typical piece of military hardware, with a service life of 20 years, can have operation and maintenance costs 60 to 80 percent of the life cycle cost.

Life cycle costing has been combined with life cycle assessment (see Sec. 8.9) of the costs of energy consumption and pollution during manufacture and service, and the costs of retiring the product when it reaches its useful life. Expansion of the cost models beyond the traditional bounds to include pollution and disposal is an active area of research that will place the design engineer in a better position to make critical trade-off decisions.

Typical elements in the life cycle of a product are shown in Fig. 16.9. This figure emphasizes the overlooked impact on society costs (OISC) that are rarely quantified and incorporated into a product life cycle analysis.[35] Starting with design, the actual costs incurred here are a small part of the LCC, but the costs committed in design comprise about 75 percent of the avoidable costs within the life cycle of the product. Moreover, it is about 10 times less costly to make a change or correct an error in design than in manufacturing. Acquiring the raw materials, usually by mining or oil extraction, and processing the materials, can create large environmental costs. These areas also often have considerable inventory and transportation costs. We have concentrated in previous sections on the costs in manufacturing and assembly of products.

The cost of ownership of a product is the traditional aspect of LCC. Useful life is commonly measured by cycles of operation, length of operation, or shelf life. In design we attempt to extend life for use and service by using durable and reliable materials and components. Product obsolescence is dealt with through modular products.

Maintenance costs, especially maintenance labor costs, usually dominate other use/service costs. Most analyses divide maintenance costs into scheduled or preventive maintenance and unscheduled or corrective maintenance. The mean time between failure and the mean time to repair are important parameters from reliability theory

34. MIL-HDBK 259, Life Cycle Costs in Navy Acquisitions.
35. N. Nasr and E. A. Varel, "Total Product Life-Cycle Analysis and Costing," *Proceedings of the 1997 Total Life Cycle Conference,* P-310, pp. 9–15, Society of Automotive Engineers, Warrendale, PA, 1997.

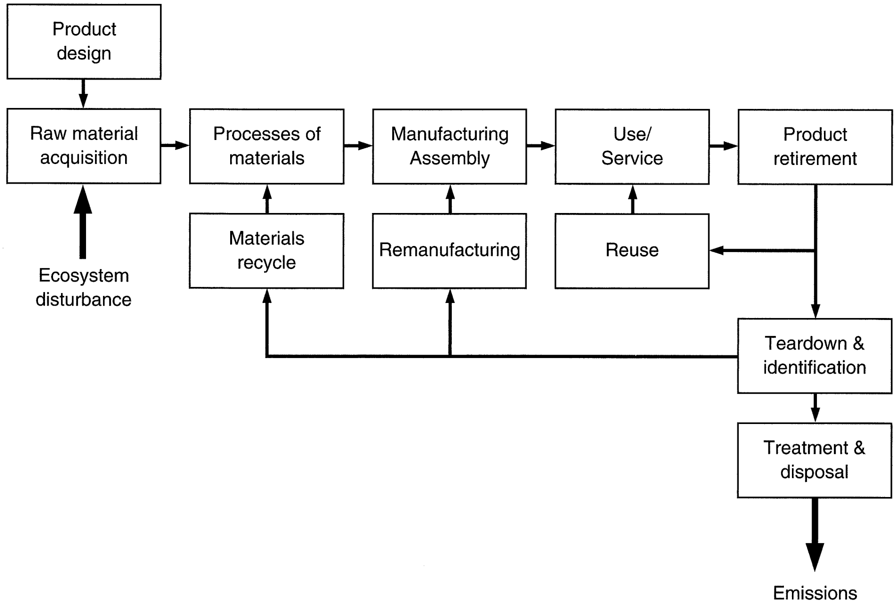

FIGURE 16.9
Total life cycle of a product.

(see Sec. 14.3.6) that affect LCC. Other costs that must be projected for the operations and support phase are maintenance of support equipment, maintenance facility costs, pay and fringe benefits for support personnel, warranty costs, and service contracts.

Once the product has reached the limit of its useful life it enters the retirement stage of the life cycle.

We saw in Sec. 8.9 that other options than disposal should be considered at the end of the product life cycle. High-value-added products may be candidates for remanufacturing. By value added we mean the cost of materials, labor, energy, and manufacturing operations that have gone into creating the product. Products that lend themselves to recycling are those with an attractive reclamation value, which is determined by market forces and the ease with which different materials can be separated from the product. Reuse components are subsystems from a product that have not spent their useful life and can be reused in another product. Materials that cannot be reused, remanufactured, or recycled are discarded in an environmentally safe way. This may require labor and tooling for disassembly or treatment before disposal.

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EXAMPLE 16.14 Life Cycle Costing
The costs and income for a product development project to design and make a short-turning-radius lawnmower are given in the following chart. It is assumed that the product will be obsolete 10 years after the start of the development project. The corporate rate of return is 12 percent and its tax rate is 35 percent. Use the concepts of the time value of

money* to find the net present value (NPV) of the project and the average annual profit margin based on sales.

Category	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10	Avg.
1. Development costs	0.8	1.90	0.4	0.4	0.4	0.4	0.4	0.2	0.2	0.2	
2. Cost of product sold			12.0	13.5	15.0	16.1	16.8	16.0	15.2	15.3	14.8
3. Sales & marketing			2.1	3.0	3.5	2.8	2.7	2.8	2.9	2.6	2.8
4. G&A plus overhead			0.8	1.5	2.0	2.0	2.0	2.0	2.0	2.0	1.7
5. Special production equipment, P		4.1									
6. Salvage value, S										0.5	
7. Depreciation on equip.		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
8. Environ. cleanup										1.1	
9. Net sales			28.2	31.3	36.2	39.8	40.0	39.1	38.0	35.0	35.95

All figures in millions of dollars.

Present Value of Costs

(1) PV of development costs = 0.8(P/F,12,1) + 1.90 (P/F,12,2) + 0.4(P/A,12,5)(P/F,12,2) + 0.2(P/A,12,3)(P/F,12,7) = \$3.47M
(2) PV of cost of product sold = 14.8(P/A,12,8)(P/F,12,2) = \$58.7M
(3) PV of sales and marketing costs = 2.8(P/A,12,8)(P/F,12,2) = \$11.17M
(4) PV of G&A and overhead = 1.7(P/A,12,8)(P/F,12,2) = \$6.73M
(5) Annual straight-line depreciation charge on (5), year 2 through 10 = $(P - S)/n = (4.1 - 0.5)/9 = 0.40$.
(7) PV of depreciation = 0.4(P/A,12,9)(P/F,12,1) = \$1.90M
(8) PV of cost of environmental cleanup = 1.1(P/F,12,10) = \$0.35M

Present value of total costs = 3.47 + 58.70 + 11.17 + 6.73 + 1.90 + 0.35 = \$82.32

Present Value of Income or Savings

(9) Present value of net sales = 35.95(P/A,12,8)(P/F,12,2) = \$130.8M
Present value of sale of equipment for salvage PV = 0.5(P/F,12,10) = \$0.16M
Present value of tax reduction (0.35)(1.90) = \$0.66M
Present value of total income or savings = \$131.6M

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* The concepts of engineering economy, based on time value of money are considered in Chap. 18 found at the text website, www. mhhe.com/dieter.

Net present value = present value of income − present value of costs = 131.6 − 82.3 = \$ 49.3M over 10 years, or an average of \$ 4.93M per year

Annual profit margin = 4.93/35.95 = 13.7% per year

Note that an average of annual income and cost was used to simplify calculation. The use of a spreadsheet would have given more accurate numbers, but this is not warranted by the precision of the estimates.

16.14 SUMMARY

Cost is a primary factor of design that no engineer can afford to ignore. It is important to understand the basics of cost evaluation so that you can produce high-functioning, low-cost designs. Cost buildup begins in conceptual design and continues through embodiment and detail design.

To be cost literate you need to understand the meaning of such concepts as nonrecurring costs, recurring costs, fixed costs, variable costs, direct costs, indirect costs, overhead, and activity-based costing.

Cost estimates are developed by three general methods.

1. Cost estimation by analogy with previous products or projects. This method requires past experience or published cost data. Because this uses historical data, the estimates must be corrected for price inflation using cost indexes, and for differences of scale using cost-capacity indexes. This method is often used in the conceptual phase of design.
2. The parametric or factor approach uses regression analysis to correlate past costs with critical design parameters like weight, power, and speed, Software programs that use parametric relationships and cost databases are becoming increasingly useful for the calculation of costs in conceptual and embodiment design.
3. A detailed breakdown of all the steps required to manufacture a part with an associated cost of materials, labor, and overhead for each step for each operation is needed to determine the cost to produce the part. This method is generally used in the final cost estimates in the detail design stage.

Costs may sometimes be related to the functions performed by the design. This is a situation highly to be desired, because it allows optimization of the design concept with respect to cost.

Manufacturing costs generally decrease with time as more experience is gained in making a product. This is known as a learning curve.

Computer cost models are gaining in use as a way to pinpoint the steps in a manufacturing process where cost savings must be achieved. Simple spreadsheet models are useful for determining product profitability and making trade-offs between aspects of the business situation.

Life cycle costing attempts to capture all the costs associated with a product throughout its life cycle, from design to retirement from service. Originally LCC focused only on the costs incurred in using a product, such as maintenance and repair, but more and more LCC is attempting to capture the costs that affect society from environmental issues and issues of energy use.

NEW TERMS AND CONCEPTS

Activity-based costing
Break-even point
Cost commitment
Cost index
Design to cost
Fixed cost
Functional costing
General & administrative costs
Indirect costs
Learning curve
Life cycle costs
Make-buy decision
Overhead cost
Period costs
Prime cost
Product costs
Target costing
Value analysis

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PROBLEMS AND EXERCISES

16.1. In an environmental upgrade of a minimill making steel bar, it is found that a purchase must be made for a larg.e cyclone dust collector. It is the time of the year for capital budget submissions, so there is no time for quotations from suppliers. The last unit of that type was purchased in 1985 for $35,000. It had a 100 ft^3/min capacity. The new installation in 2007 will require 1000 ft^3/min capacity. The cost escalation for this kind of equipment has been about 5 percent per year. For budget purposes, estimate what it will cost to purchase the dust collector.

16.2. Many consumer items today are designed in the United States and manufactured overseas where labor costs are much lower. A middle range athletic shoe from a name brand manufacturer sells for $70 in the U.S. The shoe company buys the shoe from an offshore supplier for $20 and sells it to the retailer for $36. The profit margin for each unit in the chain is: supplier—9 percent, shoe company—17 percent; retailer—13 percent.

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