Determining Manufacturing Costs

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Making early estimates of a product's cost components enables developers to manage resources wisely and evaluate the product's economic viability.

Estimating manufacturing costs of a new product or process soon after research and development (R&D) has commenced can provide a good indication of the project's economic viability. "Early" estimates can be used to direct research efforts to promising opportunities for cost reduction, and allow businesses to better assign resources to new products.

Although potentially compromised because some information may be missing, early estimates are often sufficiently accurate to shed light on a product's long-term viability.

Quick determination of the relative contribution of variable costs, fixed operating costs, and capital depreciation to the total product costs allows cost-reduction efforts to be focused on those cost components that are likely to be most significant. Because the tasks required to develop cost estimates are virtually the same for all products, time invested in developing a generalized and consistent methodology for making cost assessments and comparisons can pay large dividends.

In this article, the term "economics" is not used because cost assessments, which play a significant role in project economics, must be combined with information about the revenue the product is expected to generate. For example, the value of a new toothpaste formulation must be determined by those with knowledge of its market. Many technical personnel do not have the expertise required to address all relevant economics questions. The income side of the ledger can have a greater impact on a product's success than the items on the cost side.

Table 1. Example of variable and fixed production costs.

Variable Costs	Fixed Costs	
Raw Materials	Capital Depreciation	Supplies (office, janitorial, etc.)
Waste Treatment	Labor (both operations and supervisory)	Plant Support (*e.g.*, R&D personnel dedicated to plant troubleshooting)
Utilities (for large-volume processes)	Utilities (for small-volume processes)	Site Services (*e.g.*, plant security, support of plant infrastructure)
	Plant Maintenance	

A great deal of information has been published on methods of estimating manufacturing costs. However, much of this work has addressed the costs of a specific product or process or has concentrated on capital equipment and its depreciation, which is only one component of total product cost.

Cost components. Product manufacturing costs can be categorized as fixed or variable (Table 1). Those that are insensitive to the volume of product made are considered to be fixed. Labor, although not completely fixed, is somewhat independent of product volume, since the number of people operating a plant and their salaries are not easily adjusted as demand fluctuates. Raw material costs are variable — if more product is to be made, more raw material is required.

No cost is completely fixed or completely variable. Although labor is considered to be a fixed cost, personnel supply can be adjusted in response to anticipated seasonal product demand. Prices for raw materials fluctuate slightly with changes in demand. However, for estimates made in the early stages of a product's development or for the purpose of high-level decision-making, determining which costs are largely fixed and which are largely variable, and then assigning them complete dependence or independence from production volume, will facilitate the development and use of a cost-estimating method.

Estimating variable costs

Raw material usage. A simple material balance and flowsheet must be developed in order to estimate the variable costs of raw materials. Spreadsheets are useful tools for this purpose, and, once created, can be appended to cost worksheets for easy retrieval. The importance of effective documentation cannot be overstated. Cost estimation typically results in unpopular decisions that are frequently challenged. Confidence about exactly what was estimated is invaluable during such discussions.

The material balance may be subject to uncertainties, such as reaction yields or catalyst usage. Treating these quantities as variables and locating them in a convenient place in a spreadsheet is helpful. Use a single worksheet that can be populated

Example 1. Medium-to large-volume product
Assume:

Production Volume	= 5 million lb/yr
Required Capital Investment (correlation)	= $50 million
Total Significant Operating Sections	= 3
Waste Generation	= 3 lb aqueous waste/lb product + 0.5 lb organic waste/lb product

a. Raw Material Cost

Raw Material	Usage Rate (lb/lb of product)	Price ($/lb raw material)	Cost Contribution ($/lb product)
A	1.2	$1.50	$1.80
B	2.0	$2.50	$5.00
C (catalyst)	0.001	$200.00	$0.20
Total Raw Material Cost			= $7.00

b. Waste Treatment Cost

Total Waste Treatment Cost = (3.0 × $ 0.01/lb) + (0.5 × $ 0.20/lb)
= $0.11/lb product

c. Capital Depreciation

(from Eq. 2) Depreciation = $50,000,000 / [(10 yr × 5,000,000 lb/yr)] = $1.0/lb

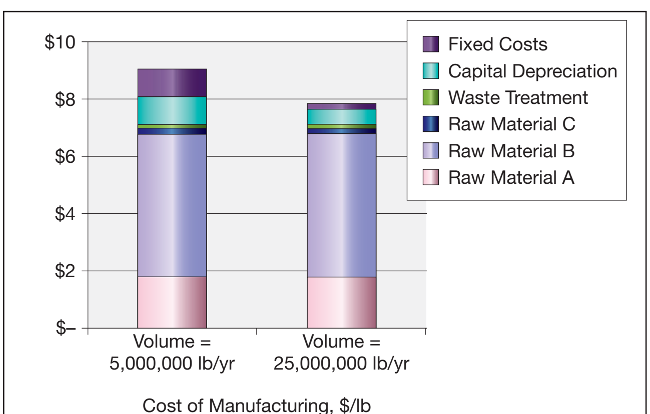
d. Other Fixed Costs

Using data from Table 2:

Operating Labor Cost	= 3 operating personnel/shift × 4 shifts × $75,000/yr = $900,000/yr
Non-Operating Labor Cost	= 0.6 × $900,000/yr = $540,000/yr
Supplies	= 0.3 × $900,000/yr = $300,000/yr
Administration/Overhead	= 0.9 × $900,000/yr = $810,000/yr
Maintenance	= 0.02 × $50,000,000 = $1,000,000/yr
Utilities	= 0.01 × $50,000,000 = $500,000/yr
Miscellaneous	= 0.01 × $50,000,000 = $500,000/yr
Total Annual Fixed Costs	= $4,550,000/yr
Total Fixed Costs	= ($4,550,000/yr) / (5,000,000 lb/yr) = $0.91/lb

e. Total Manufacturing Cost

Total Manufacturing = $7.00/lb + $0.11/lb + $1.00/lb + $0.91/lb = $9/lb



■ Figure 1. Early-phase estimates for Example 1 use a limited number of significant digits to underscore uncertainty. Since Raw Material B contributes more than 50% of total product cost, efforts should focus on reducing its usage by yield improvement, etc.

with inputs for variables whose values are expected to change. Key outputs can be placed on the same sheet to simplify the study of changes.

Areas of uncertainty can easily be explored through "what-if" questions. A project team often includes an expert whose guess-work can approximate the value of variables sufficiently for the estimator to proceed. Completion of a cost estimate using educated guesses often reveals that the importance of some variables is small because their impact on total cost is also small.

Raw material prices. Once the material balance is established, raw material prices must be identified. For those materials that are produced internally or are already purchased, pricing data can be obtained from purchasing or commercial departments. Some pricing information is available free or by subscription from sources such as *ICIS Chemical Business* (formerly *Chemical Market Reporter*), SRI Consulting (www.sriconsulting.com), Chemical Market Associates, Inc. (www.cmaiglobal.com), *Chemical Week* (www.chemweek.com), The Plastics Web (www.ides.com) and reference texts such as the "Kirk-Othmer Encyclopedia of Chemical Technology" and "Ullman's Encyclopedia of Industrial Chemistry." Many prices fluctuate widely, so using time-weighted averages is recommended.

Specialty products (*e.g.*, fine chemicals, pharmaceutical raw materials, etc.) often require raw materials that are not widely available in the marketplace. For these, a supplier inquiry is necessary. This task can be cumbersome, as many suppliers are reluctant to quote prices for projects that they consider speculative. The price of such raw materials will always depend on the volume and quality required, as well as on the project's timeframe. Some speculation is necessary. Suppliers appreciate honesty when they are asked to spend time developing pricing for products that are not off-the-shelf items.

To find the appropriate supplier, use catalogs to obtain a Chemical Abstracts Registry Number (CAS No.), which can be input as a search term on such websites as ChemNet (www.chemnet.com), Chemcompass (www.chemcompass.com), and the subscription-only Directory of World Chemical Producers. This will yield a list of companies claiming to produce each compound. Cursory knowledge of how to make a given compound can be helpful for identifying legitimate suppliers. Research can usually reveal which companies have the required know-how and can offer dependable price estimates. Be wary of suppliers claiming to have the ability to make everything. To eliminate the need to make repeated inquiries and reduce estimating time, maintain a database of pricing information collected from suppliers.

If a raw material price seems impossible to find, it may make sense to estimate as if it were to be made internally. The risk of error with this approach can be reduced if a knowledgeable colleague can suggest an efficient production method. Estimating techniques used for evaluating the final product can be applied to a raw material for which pricing information is unavailable.

It is often unwise to consult laboratory supplier catalogs for commercial pricing information. These suppliers invest heavily in inventories and packaging that suits the needs of lab-scale customers. These listed costs do not scale well.

Example 1 in the box at the left shows that increasing volume results in dramatic reduction of capital and fixed costs on a per-lb basis because these costs are not strong functions of volume in most chemical processes.

Cost distribution for the same product at a much higher volume is shown on the right of Figure 1. For this case, capital (Eq. 1) is $131 million. The product cost is not impacted significantly because it is dominated by the cost of raw materials. This is typical for large-volume products.

For Example 2, as volume increases to 500,000 lb/yr, capital (Eq. 1, as discussed on p. 30) becomes $105 million, demonstrating that fixed costs have a significant impact on the cost of small-volume products. Fixed costs increase logarith-mically (since volume is the denominator in cost-per-lb computations). A valid volume forecast is most critical at lower production rates. Uncertainties associated with the technical inputs (*e.g.,* yields, capital) can be very small compared to the uncertainty that results from invalid volume forecasts.

Waste treatment. The amount of waste produced must be known in order to determine waste-treatment charges, which depend on the material balance. The waste-disposal cost depends on the nature of the waste, as well as whether a commercial or municipal treatment plant can handle it or investment in onsite waste-treatment equipment is needed. When project-specific data are unavailable, published methods for estimating the cost of treatments can be used (*1*). It is unlikely that a commercial or municipal treatment facility will make dramatic capacity increases to accommodate every new process/customer; in many cases, such increases are impossible. Thus, it may be necessary to include waste-treatment facilities in the estimate. Waste-treatment equipment (*e.g.,* a vent incineration system) is often expensive to build and operate.

Utilities. For many projects, utility costs are significant and must be estimated based on an energy balance. Useful methods that consider the varying cost of fuel have been published (*1*). The cost of utilities generated from natural gas and coal (such as steam and electricity) vary considerably with location.

For small-volume products, utility usage rates can be very small. In such cases, the cost of utilities is largely fixed in nature: the cost of maintaining and operating a site utility system can be the largest share of the plant's utility cost. In these cases, it is reasonable to estimate the total utility cost as a function of the plant's capital. A value of 2% of the plant's capital for an overall utility cost is reasonable for such processes (*e.g.,* the annual utility costs for a plant that cost $50 million to construct would be approximately $1 million per year). This utility estimate is very rough and should be reserved for cases where utility costs are known to be small, but it is often adequate for cost estimates for very specialized products.

Example 2. Small-volume product

Assume:

Production Volume	= 100,000 lb/yr + 500,000 lb/yr
Required Capital Investment (correlation)	= $40 million
Total Significant Operating Sections	= 5
Raw materials	= $7.00/lb product
Waste Generation	= 20 lb aqueous waste/lb product + 5 lb organic waste/lb product

a. Waste Treatment Cost

Total Waste Treatment Cost	= (20.0 × $0.01/lb) + (5 × $0.20/lb) = $1.20/lb product

b. Capital Depreciation

Estimated Capital	= $40 million
Projected Sales Volume	= 100,000 million lb/yr
Depreciation (from Eq. 2)	= $40,000,000 / [(10 yr × 100,000 lb/yr)] = $40/lb

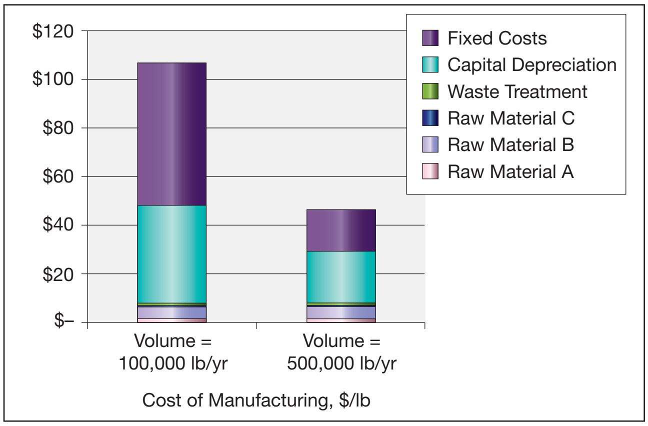
c. Other Fixed Costs

Using data from Table 2:

Operating Labor Cost	= 5 operating personnel/shift × 4 shifts × $75,000/yr = $1,500,000/yr
Non-Operating Labor Cost	= 0.6 × $1,500,000/yr = $900,000/yr
Supplies	= 0.3 × $1,500,000/yr = $450,000/yr
Administration/Overhead	= 0.9 × $1,500,000/yr = $1,350,000/yr
Maintenance	= 0.02 × $40,000,000 = $800,000/yr
Utilities	= 0.01 × $40,000,000 = $400,000/yr
Miscellaneous	= 0.01 × $40,000,000 = $400,000/yr
Total Annual Fixed Costs	= $5,800,000/yr
Total Fixed Costs	= ($5,800,000/yr) / (100,000 lb/yr) = $58/lb

d. Total Manufacturing Cost

Total Manufacturing	= $7.00/lb + $1.20/lb + $40/lb + $58/lb = ~$106/lb



■ Figure 2. The cost distribution for Example 2 shows a dramatic reduction in capital and fixed costs on a "per lb" basis. A valid volume forecast is always important, but is most important for cases where volume begins to approach zero.

Estimating fixed capital costs

Capital estimation is treated in a number of textbooks and articles (*2–7*). Many techniques are available for developing capital cost estimates, including a variety of commercially available software packages. Unfortunately, many of these methods are equipment-based, so a list of the specific items required by the process must be available along with at least some fundamental information (*e.g.,* size, capacity) about each.

For early-stage estimates, this information is difficult to obtain or develop. A much more significant problem is that equipment-based estimates depend on the completeness of the equipment list. In early stages of a product's development, the equipment list is always incomplete. For example, an equipment list for such a product is unlikely to include a filter that removes black specks if the black specks in question have not yet been observed in laboratory work. Likewise, the need for a column would not be considered in an equipment list made before an

Table 2. Relative complexity of common unit operations.

Operation	Relative Complexity	Operation	Relative Complexity
Reaction/Workup			
Gas stripping (sparge from separate vessel)	0.60	Crystalllizer (separate vessel)	1.00
Secondary reaction (neutralization, post cooking)	0.80	Decantation (seprate vessel)	0.90
Reaction	1.00		
Separation			
Atmospheric distillation (no tower)	1.20	Leaf or plate-and-frame type filtration (no solids packing; no slurry tank)	0.30
Atmospheric distillation (with tower)	1.40	Centrifugation (no solids packing; no reslurry tank)	1.50
Vacuum distillation (no tower)	1.40	Dryer	1.30
Candle filtration (no solids packing; no reslurry tank)	0.60	Vacuum distillation (with tower)	1.60
Solids Handling			
Size enlargement	1.30	Centrifugation (isolate solids in packs)	1.60
Drum, pack or bag handling	0.20	Mills, crushers, grinders	0.50
Filtration (isolate solids in packs)	0.60	Centrifuge (biochemical stack disk, decanter)	2.00
Storage and Transfer			
Conveyors	0.10	Intermediate processing tank (reslurry tank, etc.)	0.50
Raw materials storage, unloading, handling, transfer	0.50	Intermediate storage (solvents for recycling, surge tanks, etc.)	0.40
Utility			
Unloading station	0.30	Hot oil system	0.50
Demineralized water generation system	0.30	Cooling tower	0.30
Refrigeration unit	1.30	Thermal treatment unit, including fume scrubber	2.50
Waste Handling			
Carbon adsorption (gases; cannisters)	0.10	Process fume scrubbing	0.60
Carbon adsorption (liquid)	0.80		

R&D team realizes that a separation is necessary.

This problem can be reduced by using higher-level techniques based on existing operational plants and processes. Since such uncertainties have presumably been eliminated in plants that are already running, estimates that extrapolate from them include the cost of all items implicitly (even those for which the need is not initially obvious).

Methods for capital-cost estimation that require less information are indispensable for early stages of process/prod-uct development. Data on the capital invested in a large number of existing plants and processes are available in reports available by subscription from SRI Consulting, Chem Systems (www.chemsystems.com), and government laboratories, such as the National Renewable Energy Laboratory (NREL; www.nrel.gov) and the National Energy Technology Laboratory (www.netl.doe.gov). These can be used for rough comparisons when the process is similar to one for which data are published.

Information collected by the company from past projects should be retained. These data from existing plants can be used to develop crude, but useful, correlations of capital costs as a function of various factors, including: number of unit operations, volume, location, materials of construction, and operating conditions.

The Viola method captures the effects of these variables and has proven useful (*6*). In general, the variable that most often differentiates one process from another is process complexity. Means for quantifying this, by estimating the number of unit operations or reaction steps, are imperative. Table 2 can serve as a rough guideline for the relative capital investment required for some of the operations encountered in chemical processing plants, including small auxiliary items required for operation, *e.g.,* the numbers for distillation systems reflect the need for a reboiler, condenser, etc.

The effect of volume on capital is known to be nonlinear. The predictions presented in (Ref. 6) underscore this point. A common guideline for extrapolation of a capital estimate to a different volume is the six-tenths rule:

$$C_{Vy} = C_{Vx}\left(\frac{V_y}{V_x}\right)^{0.6} \tag{1}$$

where C_{vy} is capital at volume y, C_{vx} is capital at volume x, V_y is volume y, and V_x is volume x. Many references include tables that suggest refinements of this rule (*2–4, 8–10*).

The effect of location is not considered in Viola's method, nor is it within the scope of this article. It is frequently a strong function of local labor rates and, in some cases, import taxes, which vary widely with respect to both time and region.

Materials of construction costs are increasing rapidly, owing, in part, to the large amount of construction occurring in China and India, which has resulted in materials shortages. Thus, it is necessary to update this information frequently. Equipment suppliers can often provide guidance on this. The net effect of increasing material costs is lessened somewhat when calculations reflect the installed cost of a fully fabricated piece of equipment, and not simply the cost of the material in its raw form (*e.g.,* sheet metal).

Corrections for extreme operating conditions (*i.e.,* temperatures greater than 200ºC or less than –10ºC, pressures greater than 200 psia or less than atmospheric) typically add 10–20% to the total capital cost computed by this method. This relatively minor impact results from the fact that much of the cost of any equipment item is independent of the amount of material used to build it (*e.g.,* installation and instrumentation costs are somewhat insensitive to operating conditions).

Capital depreciation. Depreciation calculations assign some fraction of the plant investment to each unit of product made. For early-stage estimates, it is convenient to assume a 10-yr plant life with a constant rate of recovery. This is known as a 10-yr, straight-line calculation and is represented by:

$$D = \frac{C}{(10)(V)} \tag{2}$$

where D is depreciation ($/lb), C is capital ($), V is production volume (lb/yr), and *10* (yr) is the plant life for the example.

Equation 2 can give an initial estimate for capital depreciation and, when applied to a variety of projects, will yield a reasonable basis of comparison. This is not the method commonly used to calculate depreciation for tax purposes.

Estimating other fixed costs

Many fixed costs are related to (and can be predicted from) the capital required to construct the plant. Labor cost varies considerably with the type of process being considered. Methods of estimating labor costs have been published (*11–13*). Many costs vary predictably with either labor cost or capital investment. Table 3 provides guidelines for estimating fixed costs as a function of capital or operating cost.

A rough assessment of the operating tasks required by the process can help suggest the number of people required. One person per shift will often be needed for each significant plant operation — *i.e.*, a process that includes a raw-material handling section, a reaction section, a separation section, and a packaging section would require four operating personnel. If 24-h operation is planned and personnel are to have two days off per week, then each operating "job" requires four full-time personnel, so the example process requires 16 operating personnel (four per shift, with three shifts "on" and one shift taking a two-day rest).

Chemical process operations commonly employ between two and six operating personnel per shift. Investment in instrumentation and automation reduces the number of people needed to run a plant. Review past practices of the department or company sponsoring the project to develop a more-realistic estimate.

The cost of operating labor is very dependent on plant location. In the U.S., it is reasonable to assume an annual cost of $75,000 per person. If available, company data should be used.

Table 3. Rules of thumb for computing fixed costs.

Operating labor	= 2 to 6 persons per shift x 4 shifts x $75,000/year
Non-operating labor, *e.g.,* technical support	= 0.60 x Cost of Operating Labor ($/yr)
Supplies (*e.g.,* office items, protective equipment, etc.)	= 0.30 x Cost of Operating Labor ($/yr)
Administration	= 0.90 x Cost of Operating Labor ($/yr)
Utilities (compute using energy balance)	= 0.02 x Capital Investment ($)
Maintenance	= 0.02 to 0.06 x Capital Investment ($)
Miscellaneous (*e.g.,* taxes, insurance)	= 0.01 to 0.02 x Capital Investment ($)

In summary

An early-stage estimate prepared using these guidelines will require adjustments as information is collected. Reaction yields, raw material prices, equipment details, plant location, and many other variables will be established as the project progresses, allowing the estimate to be improved. Eventually, more-sophisticated estimating techniques should be used.

However, if the assumptions used to make the initial estimate are reasonable, projects that are clearly uneconomical can be removed from the R&D portfolio. For instance, in the first example, the estimator could state with some confidence that the product must command a price of more than $9/lb in the marketplace if it is to be a commercial success. Projects that have commercial viability can be more quickly optimized using a rough cost distribution. CEP

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